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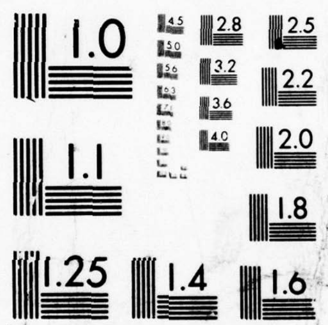

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This paper reports on research comparing various approaches, or methodologies, for software development. The study focuses on the quantitative analysis of the application of certain methodologies in an experimental environment, in order to further understand their effects and better demonstrate their advantages in a controlled environment. A series of statistical experiments were conducted comparing programming teams that used a disciplined methodology (consisting of top-down design, process design language usage, structured programming, code reading, and chief programmer team organization)

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20. Abstract continued.

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INVESTIGATING SOFTWARE DEVELOPMENT APPROACHES *

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Abstract:
This paper reports on research comparing various approaches, or methodologies, for software development. The study focuses on the quantitative analysis of the application of certain methodologies in an experimental environment, in order to further understand their effects and better demonstrate their advantages in a controlled environment. A series of statistical experiments were conducted comparing programming teams that used a disciplined methodology (consisting of top-down design, process design language usage, structured programming, code reading, and chief programmer team organization) with programming teams and individual programmers that employed ad hoc approaches. Specific details of the experimental setting, the investigative approach (used to plan, execute, and analyze the experiments), and some of the results of the experiments are discussed.

Key words and Phrases:
analysis of software development, disciplined methodology, programming teams, experimental study, program measurements, software metrics

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I. Introduction

In the development of any theory, there are three phases of validation. First is the logical development of the theory based on a set of sound principles. Second is the application of the theory and the gathering of evidence that the theory is applicable in practice. This usually involves some qualitative assessment in the form of case studies. The third step is the quantitative analysis of the application of theory in an experimental environment in order to further understand its effect and better demonstrate its advantages in a controlled environment.

There has been a great deal written about methodologies and programming environments for developing software [Wirth 71; Dahl, Dijkstra, and Hoare 72; Jackson 75; Brooks 75; Myers 75; Linger, Mills, and Witt 79]. It is clear that many of these methodologies are based on sound logical principles and their adoption within a production environment has been successful. There have been many case studies that attempt to validate these theories; projects have adapted versions of these methods and have reported varying degrees of success, i.e., the users feel they got the job done faster, made less errors, or produced a better product [Baker 75; Basili and Turner 75; Daley 77]. Unfortunately, there has been a minimum of real quantitative evidence that comparatively assesses any particular methodology [Shneiderman et al. 77; Myers 78; Sheppard et al. 78]. This is partially because of the cost and impracticality of a valid experimental setup within a production ("real-world") environment.

This leaves open the question of whether there is a measurable benefit derived from various programming methodologies and environments with respect to either the developed product or the development process. Even if the benefits are real, it is not clear that they can be quantified and effectively monitored. Software development is still too much of an art in the aesthtic or spontaneous sense. In order to fully understand it, control it, and adapt it to particular applications and situations, software development must become more of a science in the engineering and calculated sence. What is required is more empirical study, data collection, and experimental analysis.

The purpose of the research reported in this paper is (a) to quantitatively investigate the effect of methodologies and programming environments on software development and (b) to develop an investigative methodology based on scientific experimentation and tailored to this particular application. It involves the measurement and analysis of both the process and the product in a manner which is minimally obtrusive (to those developing the software), very objective, and highly automatable. The goal of the research was to verify the effectiveness of a particular programming methodology and to identify various quantifiable aspects that could demonstrate such effectiveness.

To this end, a controlled experiment was conducted involving several replications of a specific software development task under varying programming environments. For each replication successive versions of the software under development were entered in an historical data base which recorded details of the development process and product. A host of measurements were extracted from the data base and statistically analyzed in order to achieve the research goals. Some of these measurements were "confirmatory", as they were planned in advance and expected to show differences among the programming environments being investigated, while many of the measurements were simply "exploratory."

The study involves three distinct groupings of software developers: individual programmers, ad hoc three-person programming teams, and three-person programming teams using a disciplined methodology. The individual programmers and the ad hoc teams were allowed to develop the software in a manner of their own choosing; this is referred to as an ad hoc approach. The disciplined methodology referred to in this paper consists of an integrated set of software development techniques and team organizations which include top-down design, use of a process design language, structured programming, code reading, and chief programmer teams.

The study examines differences in the <u>expectency</u> and the <u>predictability</u> of software development behavior under the programming environments represented by these groups.

The basic premise is that distinctions among the groups exist both in the <u>process</u> and in the <u>product</u>. With respect to the software development product, it is believed that the disciplined team should approximate the single individual with regard to product characteristics (such as number of decisions coded and global data accessibility) and at the very least lie somewhere between the single individual and the ad hoc team. This is because the disciplined methodology should help in making the team act as a mentally cohesive unit during the design, coding, and testing phases. With respect to the software development process, the disciplined team should have advantages over both individuals and ad hoc teams, displaying superior performance on cost factors such as computer usage and number of errors made. This is because of the discipline itself and because of the ability to use team members as a resource for validation.

The study's findings reveal several programming characteristics for which statistically significant differences do exist among the groups. The disciplined teams used fewer computer runs and apparently made fewer errors during software development than either the individual programmers or the ad hoc teams. The individual programmers and the disciplined teams both produced software with essentially the same number of decision statements, but software produced by the ad hoc teams contained greater numbers of decision statements. For no characteristic was it concluded that the disciplined methodology impaired the effectiveness of a programming team or diminished the quality of the software product.

The investigation has been conducted in a laboratory or proving-ground fashion, in order to achieve some statistical significance and scientific respectability without sacrificing production realism and professional applicability. By scaling down a typical production environment while retaining its important characteristics, the laboratory setting provides for a reasonable compromise between the extremes of

(a) "toy" experiments,

which can afford elaborate experimental designs and large sample sizes but often suffer from a basic task that is rather unrelated to production situations or involve a context from which it is difficult to extrapolate or scale up (e.g., introductory computer course students taking multiple-choice quizzes based on thirty-line programs),

and (b) "production environment" experiments,

which offer a high degree of production realism by definition but incur prohibitively high costs even for the simplest and weakest experimental designs (i.e., statistical experimentation requires replication, and multiple duplication of a nontrivial programming project is clearly expensive).

The experiment in this study was conducted within an academic environment where it was possible to achieve an adequate experimental design and still simulate key elements of a production environment.

An initial phase of investigation has been completed and the complete results are presented in the remainder of this paper. Section II gives details pertaining to the experiment itself. Section III describes the investigative methodology used to plan, execute, and analyze the experiment. Sections IV and V present the experiment's results, segregated into empirical findings (resulting from statistical analysis of the measurements) and intuitive judgements (resulting from interpretation of some of the empirical findings), respectively. Section VI contains some remarks on this initial phase of investigative effort and a discussion of further work planned for the study.

It should be noted that the terms 'methodology' and 'methodological' (in reference to software development) are consistently used throughout this report with a technical meaning related to the concept of a comprehensive integrated set of development techniques as well as team organizations, rather than to the more common notion of a particular technique or organization in isolation.

II. Specifics

This section describes several aspects of the experiment itself; namely, the experimental design or setup, the experimental environment, data collection and reduction (during and subsequent to the experiment), and the programming aspects and associated metrics (used to quantify the experiment).

Design/Setup

The major facets of the experimental design are the experimental units, the experimental treatment factors, the experimental treatment factor levels, the experimental variables observed, the experimental local control, and the experimental management of other factors. (See [Ostle and Mensing 75; Chapter 9] for a thorough presentation of these facets.) An experimental unit is that unit to which a single treatment (which may be a combination of several factor levels) is applied in one replication of the basic experiment. In this case, the basic experiment was the accomplishment of a given software development project, and the experimental unit was the software development team, i.e., a small group of people who worked together to develop the software. There was a total of 19 such units involved in the experiment.

In most experiments, attention is focused on one or more independent variables and on the behavior of a certain dependent variable(s) as the independent variables are permitted to vary. These independent variables are known as experimental treatment factors. This experiment focused on two particular facets of software development, (1) size of the development team and (2) degree of methodological discipline, as the experimental treatment factors.

Most experiments involve some deliberate differential variation in the experimental treatment factors. The various values or classifications of the factors are known as the levels of the experimental treatment factors. In this experiment, two levels were selected for each factor. For the size factor, the levels were single individuals and three-person teams. For the degree-of-discipline factor, the levels were an ad hoc approach and a disciplined methodology.

The experimental (dependent) variables observed consisted of 130 programming aspects relating to the software product and development process. Technically, this created a whole series of simultaneous univariate experiments, all having the same common experimental design and all based on the same data sample, with one experiment for each programming aspect. The immediate goal of an experiment is to learn something about the relationship between the experimental treatment factor levels and the observed variables.

Experimental local control refers to the configuration by which (a) experimental units are obtained, (b) certain sets of units are placed into groups, and (c) these different groups are subjected to certain combinations of experimental factor levels. Local control is employed in the design of an experiment in order to increase the statistical efficiency of the experiment (or sensitivity/power of the statistical test). Experimental local control usually incorporates some form(s) of randomization --a basic principle of experimental design-- since it is necessary for the validity of statistical test procedures.

For this experiment, subjects were obtained simply on the basis of course enrollment. Since the experiment was completely embedded within two academic courses, every student in those courses automatically participated in the experiment. Development "teams" were formed among the subjects: in one course, the students were allowed to choose between segregating themselves as individual programmers or combining with two other classmates as three-person programming teams; in the other course, the students were assigned (by the researchers) into three-person teams.

Experimental units were formed and placed into groups in this manner because the two academic courses themselves provided the two levels of the second experimental treatment factor. This process yielded three groups of 6, 6, and 7 units, designated AI, AT, and DT, respectively. Each group was exposed to a particular combined factor-level treatment according to the following partial factorial arrangement: (AI) single individuals using an ad hoc approach, (AT) three-person teams using an ad hoc approach, and (DT) three-person teams using specific state-of-the-art methodologies.

The disciplined methodology imposed on teams in group DT consisted of an integrated set of techniques, including top down design of the problem solution using a Process Design Language (PDL), functional expansion, design and code reading, walk-throughs, and chief programmer and manager teams. These techniques and organizations were taught as an integral part of the course that the subjects were taking. The course material was organized around [Linger, Mills, and Witt 79], [Basili and Baker 75], and [Brooks 75] as textbooks. Since the subjects were novices in the methodology, they executed the techniques and organizations to varying degrees of thoroughness and were not always as successful as seasoned users of the methodology would be.

Specifically, the disciplined methodology prescribed the use of a PDL for expressing the design of the problem solution. The design was expressed in a top-down manner, each level representing a solution to the problem at a particular level of abstraction and specifying the functions to be expanded at the next level. The PDL consisted of a specific set of structured control and data structures, plus an open-ended designer-defined set of operators and operands corresponding to the level of the solution and the particular application. Design and code reading involved the critical review of each team member's PDL or code by at least one other member of the team. Walk-throughs represented a more formalized presentation of an individual's work to the other members of the team in which the PDL or code was explained step by step. In the chief programmer teams, the chief programmer defined the top level solution to the problem in PDL, designed and implemented the key code himself, and assigned subtasks to each of the other two programmers who code read for the chief programmer, designed or coded subpieces as requested by him, and performed librarian activities (i.e., entering or revising code stored on-line, making test runs, etc.). The manager teams were defined in a similar fashion, except that the manager also acted as librarian, writing less code and doing more code reading, and yielded much greater responsibility for design and implementation to the other members of the team.

Each individual or team in groups AI and AT was allowed to develop the software in a manner of their own choosing, which is referred to in this paper as an ad hoc approach. No methodology was taught in the course these subjects were taking. Informal observation by the experimenters confirmed that the approaches used by the individuals and ad hoc teams were indeed lacking in discipline and did not utilize the key elements of the disciplined methodology (e.g., an individual working alone cannot practice code reading, and it was evident that the ad hoc teams did not use a PDL or formally do a top-down design).

There are usually several extraneous factors, other than the ones identified as experimental treatment factors, which could influence the behavior being observed. The experimental design employed three distinct methods to control various extraneous factors. Factors were either fixed (artifically or externally held constant across all experimental units), balanced (artificially or externally distributed as evenly as possible among the experimental units), or randomized (allowed to vary in a naturally random way among the experimental units). In this experiment, a variety of programming factors which do affect software development were given conscious consideration as extraneous variables and controlled as follows:

- personal ability/talent of people: randomized

(and balanced within disciplined teams)

- project/task/application: fixed
- project specifications: fixed
- implementation language: fixed
- calendar schedule: fixed
- available computer resources: fixed
- available man-hour resources: randomized
- available automated tools: fixed

Wherever possible, these variables were held constant by explicitly treating all experimental units in the same manner. Two variables, the personal ability of the participants and the amount of actual time they (as students with other classes and responsibilities) had to devote to the project, could only be allowed to vary among the groups in what was assumed to be a random manner. However, information from a questionnaire was used to balance the personal ability of the participants in the disciplined teams (only) by first (a) partitioning the group DT students into three equal-sized categories (high, medium, low) based on their grades in previous computer courses and their extracurricular programming experience, and then (b) assigning them to teams by randomly selecting one student from each category to form each team.

Environment

Several particulars of the experimental environment contribute significantly to the context in which the experiment's results must be appraised. These include the time and place the experiment was conducted, the software development project (or application) which served as the task performed during the experiment, the people who participated as subjects, and the computer programming language in which the software was written.

The experiment was conducted during the Spring 1976 semester, January through May, within the regular academic courses given by the Department of Computer Science on the College Park campus of the University of Maryland.

Several general characteristics of the project are noteworthy. The application was a compiler, involving string processing and language translation (via scanning, parsing, code generation, and symbol table management). The scope of the project excluded both extensive error handling and user documentation. The project difficulty was slight but nonnegligible, requiring roughly a two man-month effort. The size of the resulting system averaged over 1200 lines of high-level (structured language) source code. The total task was to design, implement, test, and debug the complete computer software system given a particular specification. All aspects of the project were fixed and uniform for each of the development teams. Each team worked independently to build its own system, using identical (1) specifications, (2) computer resources allocated, (3) duration of calendar time allotted, (4) implementation language, (5) testing tools, etc.

The participants were advanced undergraduate students and graduate students in the Department of Computer Science. None were novice programmers, all had completed at least four semesters of programming course work, several were about to graduate and take programming jobs in government or industry, and a few even had as much as three years' professional programming experience. On the whole, the participants might best be described as "advanced student programmers with a bit of professional experience." The experiment was conducted within the framework of two comparable advanced elective courses, each with the same academic prerequisites. The project and the experimental treatments were built into the course material and assignments, and everyone in the two classes participated in the experiment. They were aware of being monitored, but had no knowledge of what was being observed or why. A reasonable degree of homogeneity seemed to exist among the participants with respect to personnel factors, such as ability, experience, motivation, time/effort devoted to the project, etc. On the whole, they were typically average in each of these factors with natural fluctuations which appeared to be evenly distributed among the experimental groups in a random fashion. Based upon pre-experiment qualitative judgment, all subjects shared a similar background with respect to team programming and the disciplined methodology. However, groups AI and AT (the individuals and ad hoc teams) seemed to have had a slight edge over group DT (the disciplined teams) with respect to general programming ability and formal training in the application area.

The implementation language was the high-level, non-block-structured, structured-programming language SIMPL-T [Basili and Turner 76]. This language was designed and developed at the University of Maryland where it is taught and used extensively in regular Department of Computer Science courses. It is characterized by a very simple and efficient run-time environment. SIMPL-T contains the following control constructs: sequence, ifthenelse, whiledo, case, and exits from loops (but no gotos). The language adheres to a philosophy of "strong data typing" and all variables must be explicitly declared. It provides the programmer with both automatic recursion and string-processing capabilities similar to PL/1.

<u>Data Collection and Reduction</u>

Due to the partially exploratory nature of the experiment in terms of differences to be discovered in the project and process, as much information was collected as could be done in an efficient, effective, and unobtrusive manner. A variety of information sources was used. Individual questionnaires supplied the personal background and programming experience of each participant. Private team interviews and open-class team reports yielded information regarding individual performance on the project. Run logs and computer account billing reports gave a record of the computer activity during the project. Special module compilation and program execution processors (invoked on-line via very slight changes to the regular command language) created an historical data base of source code and test data accumulated throughout the project development.

The data base provided the principal source of information analyzed in the current investigation and other information sources have been utilized only in an auxiliary manner (if at all). Thus, data collection for the experiments themselves was automated on-line, with essentially no interference to the programmer's normal pattern of actions during computer (terminal) sessions. The final products were isolated from the data base and measured for various syntactic and organizational aspects of the finished product source code. Effort and cost data were also extracted from the data base. The inputs to the analysis, in the form of scores for the various programming aspects, reflect the quantitatively measured character of the product and effort of the process. Much of the data reduction was done automatically within a specially instrumented compiler. Some was done manually (e.g., examining characteristics across modules). Due to the underlying collection and reduction mechanism, which was uniformally applied to all experimental units, the data used in the analysis has the characteristics of objectivity, uniformity, and quantitativeness and is measured on an interval scale of measurement [Conover 71; pp. 65-67].

Programming Aspects and Metrics

The dependent variables studied in this experiment are called programming aspects. They represent specific isolatable and observable features of the programming phenomenon which are highly automatable (i.e., they could be extracted or computed directly on-line from information readily obtainable from operating systems and compilers). The variables fall into two categories: process aspects and product aspects. Process aspects are related to characteristics of the development process itself, in particular, the cost and required effort as reflected in the number of computer job steps (or runs) and the amount of textual revision of source code during development. Product aspects are related to the syntactic content and organization of the symbolic source code which represents the complete final product that was developed. Examples are number of lines, frequency of particular statement types, average size of data variables' scope, etc. For each aspect there exists an associated metric, a specific algorithm which ultimately defines that aspect and by which it is measured.

The particular programming aspects examined in this investigation are listed in Table 1. They appear grouped by category; indented qualifying phrases specify particular variants of certain general aspects. When referring in this paper to an individual (sub)aspect, a concatenation of the heading line with the qualifying phrases (separated by \ symbols) is used; for example, COMPUTER JOB STEPS\MODULE COMPILATIONS\UNIQUE denotes the number of COMPUTER JOB STEPS that were MODULE COMPILATIONS in which the source code was UNIQUE from all other compiled versions. Explanatory notes (keyed to the list in Table 1) about the programming aspects are given in Appendix 1, complete with definitions for the nontrivial or unfamiliar metrics. Technical meanings for various system- or language-dependent terms used in the paper (e.g., module, segment, intrinsic, entry) also appear there. Some of these words mean different things to different people, and the reader is cautioned against drawing inferences not based on this paper's definitions.

The complete set of programming aspects may be partitioned into two subsets based upon the motivation for their inclusion in the study. Several aspects --hereafter denoted as "<u>confirmatory</u>"-- had been consciously planned in advance of collecting and extracting the data, because intuition suggested that they would serve well as quantitative indicators of important qualitative characteristics of the sofware development phenomenon. It was predicted a priori that these "confirmatory" aspects would verify the study's basic premises regarding the programming methodologies being investigated in the experiment. The remaining aspects --hereafter denoted as "<u>exploratory</u>"-- were considered mainly because they could be collected and extracted cheaply (even as a natural by-product sometimes) along with the "confirmatory" aspects. There was little serious expectation that these "exploratory" aspects would be useful indicators of differences

Table 1. Programming Aspects

N.B. The asterisks to the left mark "confirmatory" aspects; "exploratory" aspects are unmarked. The parenthesized numbers to the right refer to the explanatory notes in Appendix 1.

	development process aspects :	
*	COMPUTER JOB STEPS	(1)
*	MODULE COMPILATIONS	(2)
*	UNIQUE	(3)
	IDENTICAL	(3)
*	PROGRAM EXECUTIONS	(4)
	MISCELLANEOUS	(5)
*	ESSENTIAL JOB STEPS	(6)
	AVERAGE UNIQUE COMPILATIONS PER MODULE	(7)
	MAX UNIQUE COMPILATIONS F.A.O. MODULE	(8)
*	PROGRAM CHANGES	(9)
	final product aspects :	
*	MODULES	(10)
*	SEGMENTS	(11)
	SEGMENT TYPE COUNTS :	(12)
	FUNCTION	(11)
	PROCEDURE	(11)
	SEGMENT TYPE PERCENTAGES :	(12)
	FUNCTION	(11)
	PROCEDURE	(11)
	AVERAGE SEGMENTS PER MODULE	(13)
*	LINES	(14)
*	STATEMENTS	(15)
	STATEMENT TYPE COUNTS :	(16)
	:=	(17)
*	IF	(18)
*	CASE	(19)
*	WHILE	(20)
*	EXIT	(21)
	(PROC)CALL	(22)(44)
	NONINTRINSIC	(23)(44)
	INTRINSIC	(23)(44)
*	RETURN	(24)
	STATEMENT TYPE PERCENTAGES :	(16)
	:=	(17)
*	IF	(18)
*	CASE	(19)
*	WHILE	(20)
*	EXIT	(21)
	(PROC)CALL	(22)
	NONINTRINSIC	(23)
	INTRINSIC	(23)
*	RETURN	(24)
*	AVERAGE STATEMENTS PER SEGMENT	(25)
*	AVERAGE STATEMENT NESTING LEVEL	(26)
*	DECISIONS	(27)
	FUNCTION CALLS	(22)(44)
	NONINTRINSIC	(23)(44)
	INTRINSIC	(23)(44)

*	TOKENS	(28)
*	AVEPAGE TOKENS PER STATEMENT	(28)
	INVOCATIONS	(29)
	FUNCTION	(11)(44)
	NONINTRINSIC	(23)(44)
	INTRINSIC	(23)(44)
	PROCEDURE	(11)(44)
	NONINTRINSIC	(23)(44)
	INTRINSIC	(23)(44)
	NONINTRINSIC	(23)
	INTRINSIC	(23)
	AVG INVOCATIONS PER (CALLING) SEGMENT	(30)
	FUNCTION	(11)
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	INTRINSIC	(23)
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	INTRINSIC	(23)
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	INTRINSIC	(23)
	AVG INVOCATIONS PER (CALLED) SEGMENT	(31)(44)
	FUNCTION	(11)
	PROCEDURE	(11)
	DATA VARIABLES	(32)
	DATA VARIABLE SCOPE COUNTS :	(37)
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	ENTRY	(34)
	MODIFIED	(35)
	UNMODIFIED	(35)
	NONENTRY	(34)
	MODIFIED	(35)
	UNMODIFIED	(35)
	MODIFIED	(35)
	UNMODIFIED	(35)
	NONGLOBAL	(33)
*	PARAMETER	(33)
	VALUE	(36)
	REFERENCE	(36)
*	LOCAL	(33)
	DATA VARIABLE SCOPE PERCENTAGES :	(37)
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	NONENTRY	(34)
	MODIFIED	(35)
	UNMODIFIED	(35)
	MODIFIED	(35)
	UNMODIFIED	(35)
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*	POSSIBLE	(42)
*	RELATIVE PERCENTAGE	(42)

among the groups; but they were included in the study with the intent of observing as many aspects as possible on the off chance of discovering any unexpected tendency or difference. The "confirmatory" programming aspects are identified by being flagged in Table 1 with an asterisk; the "exploratory" programming aspects are unflagged.

This distinction between "confirmatory" and "exploratory" has important consequences for the evaluation of the study's experiments. For the "confirmatory" aspects, the individual experiments are actually confirmatory, since it was hypothesized that they would indicate certain differences among the groups, prior to conducting the experiment and extracting their scores. But for the "exploratory" aspects, whose scores were extracted without any preconcieved hypotheses, the experiments are purely exploratory. Thus, this study combines elements of both confirmatory and exploratory data analysis within one common experimental setting [Tukey 69]. This distinction does not however influence the method by which the experiments themselves were conducted.

It should be noted that a large percentage of the product aspects fall into the "exploratory" category. A secondary motivation for their consideration is that the product aspects, as a unit, represent a fairly extensive taxonomy of the surface features of software. The idea that important software qualities (e.g., "complexity") could be measured by counting such surface features has generally been disregarded by reasearchers as too simplistic (e.g., [Mills 73; p. 232]). A resolve to study these surface features empirically, to see if something might turn up, before rejecting the underlying idea, was partially responsible for their inclusion in the study.

In order to avoid any inadvertant deception or misunderstanding, the following issue of redundancy must be stated and properly appreciated. There exist several instances of duplicate programming aspects; that is, certain logically unique aspects appear a second time with another name, in order to provide alternative views of the same metric and to achieve a certain degree of completeness within a set of related aspects. For example, the FUNCTION CALLS aspect and the STATEMENT TYPE COUNTS\(PROC)CALL aspect are listed (and categorized appropriately) from the viewpoint of the various type of constructs that comprise the implementation language. But the very same metrics can be considered from the unifying viewpoint of the various subtype frequencies for segment invocations, and thus it is desirable to include the duplicate aspects INVOCATIONS\FUNCTIONS and INVOCATIONS\PROCEDURES as part of the natural categorization of INVOCATIONS. Within the 137 programming aspects listed in Table 1, there are seven pairs of duplicate aspects (identified in the notes of Appendix 1), leaving 130 nonredundant aspects examined in the study. By definition, the data scores obtained for any pair of duplicate aspects will be indentical, and thus the same statistical conclusions will be reached for both aspects. This must be kept in mind when evaluating the results of the experiments in terms of their statistical impact.

III. Approach

This section describes the steps in an investigative methodology developed for the particular problem of comparing software development efforts under various conditions. It was used to guide the planning, execution, and analysis of the experimental investigations whose results are reported in this paper.

The investigative methodology can be characterized as an empirical study based on the "construction" paradigm in which multiple subjects are closely monitored during actual "production" experiences, each subject performing the same task, with controlled variation in specific variables. It uses scientific experimentation and statistical analysis based on a "differentiation among groups by aspects" paradigm in which possible differences among the groups, as indicated by differences in certain quantitatively measured aspects of the observed phenomenon, are the target of the analysis. This use of "difference discrimination" as the analytical technique dictates a model of homogeneity hypothesis testing that influences nearly every element of the methodology.

Note that there are other analysis techniques that could have been used; e.g., estimation of magnitude of difference, correlations between various aspects (across all combinations of factor-levels), multivariate analysis (rather than multiple univariate analyses in parallel), and factor analysis (breakdown of variance) among the various aspects. These are useful techniques and may be used in later phases of this research. However, difference discrimination represents a "first-cut" probe, which hopefully will yield some information to help guide more refined probes in the future.

Although the methodology is built around an empirical study and utilizes scientific experimentation, the actual execution of the experiments and collection of data play a small role in the overall methodology when compared to the planning and analysis phases. This is readily apparent from the Approach Schematic, Diagram 1, which charts some of the relationships among the various elements (or steps) of the investigative methodology.

The remainder of this chapter outlines and briefly describes the overall approach by defining each step in general and discussing how the approach was applied in the research effort at hand. Note that Sections IV and V give the specifics of the last two steps of the approach --statistical conclusions and research interpretations-- as pertaining to the current experimental investigation.

Step 1: Questions of Interest

Several questions of interest were initiated and refined so that answers could be given in the form of statistical conclusions and research interpretations. Questions were formulated on the basis of several areas of interest: (1) software development rather than software maintenance, (2) a particular set of programming factors, (3) quantitatively measurable aspects of the process and the product, (4) two particular levels for each of the programming factors, (5) the particular type of analysis technique mentioned above, and (6) intuitive considerations and suspicions leading to choice of a particular three-way grouping of the factor-level combinations.

The final questions of interest culminated in the form "During software development, what comparisons between the effects of the three factor-level combinations (a) single individuals, (b) ad hoc teams, and (c) disciplined teams appear as differences in the various quantitatively measurable aspects of the software development process and product? Furthermore, what kind of differences are exhibited and what is the direction of these differences?"

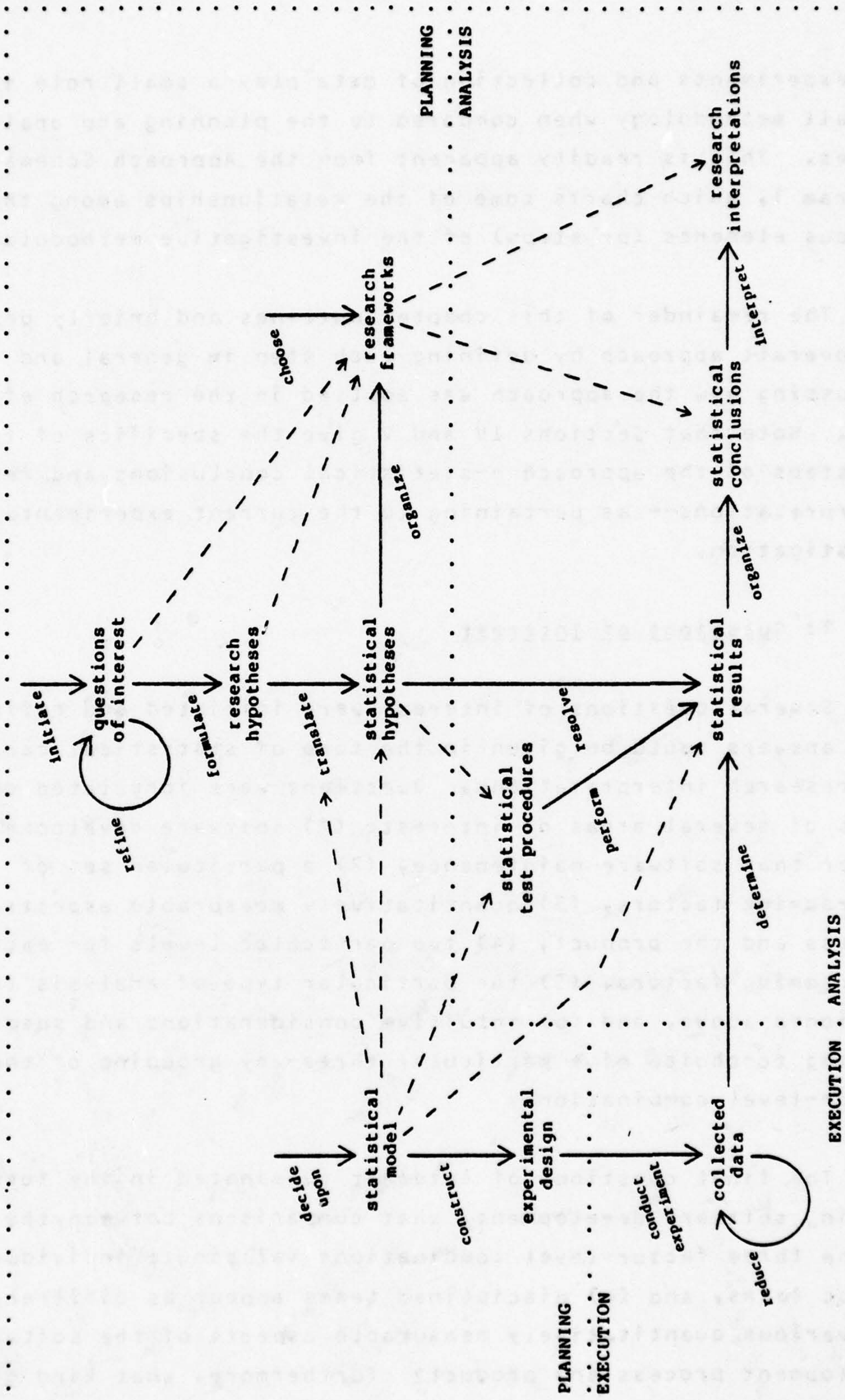


Diagram 1. Approach Schematic

Step 2: <u>Research Hypotheses</u>

Since the investigative methodology involves hypothesis testing, it is necessary to have fairly precise statements, called research hypotheses, which are to be either supported or refuted by the evidence. The second step in the approach was to formulate these research hypotheses, disjoint pairs designated null and alternative, from the questions of interest.

A precise meaning was given to the notion "what kind of difference." The investigation considered both (a) differences in central tendency or average value, and (b) differences in variability around the central tendency, of observed values of the quantifiable programming aspects. It should be noted that this decision to examine both location and dispersion comparisons among the experimental groups brought a pervasive duality to the entire investigation (i.e., two sets of statistical tests, two sets of statistical results, two sets of conclusions, etc. --always in parallel and independent of each other--), since it addresses both the <u>expectency</u> and the <u>predictability</u> of behavior under the experimental treatments.

Some vagueness was removed regarding the size of the particular programming task by making explicit the implicit restriction that completion of the task not be beyond the capability of a single programmer working alone for a reasonable period of time. Additionally, a large set of programming aspects were specified; they are discussed in Section II, Specifics. For each programming aspect there were similar questions of interest, similar research hypotheses and similar experiments conducted in parallel.

The schema for the research hypotheses may be stated as "In the context of a one-person do-able software development project, there < is not | is > a difference in the < location | dispersion > of the measurements on programming aspect < X > between individuals (AI), ad hoc teams (AT), and disciplined teams

(DT)." For each programming aspect 'X' in the set under consideration, this schema generates two pairs of nondirectional research hypotheses, depending upon the selection of 'is not' or 'is' corresponding to the null and alternative hypotheses, and the selection of 'location' or 'dispersion' corresponding to the type of difference.

Step 3: Statistical Model

The choice of a statistical model makes explicit various assumptions regarding the experimental design, such as the dependent variables observed, the distributions of the underlying populations, etc. Because the study involves a homogeneity-of-populations problem with shift and spread alternatives, the multi-sample model used here requires the following criteria: independent populations, independent and random sampling within each population, and interval scale of measurement [Conover 71; pp. 65-67] for each programming aspect. Although random sampling was not explicitly achieved in this study by rigorous sampling procedures, it was nonetheless assumed on the basis of the apparent representativeness of the subject pool and the lack of obvious reasons to doubt otherwise. Due to the small sample sizes, the unknown shape of the underlying distributions, and the partially exploratory nature of the study, a nonparametric statistical model was used.

Whenever statistics is employed to "prove" that some systematic effect --in this case, a difference among the groups-- exists, it is important to measure the risk of error. This is usually done by reporting a significance level α [Conover 71; p. 79], which represents the probability of deciding that a systematic effect exists when in fact it does not. In the model, the hypothesis testing for each programming aspect was regarded as a separate independent experiment. As a consequence of this choice, the signigicance level is controlled and reported experimentwise (i.e., on a per aspect basis). While the assumption of independence between such experiments is not entirely supportable, this procedure is valid as long as conclusions that couple one or more of these programming aspects are avoided or properly qualified. In this study, statements regarding interrelationships among aspects are made only within the interpretations in Section V.

Step 4: Statistical Hypotheses

The research hypotheses must be translated into statistically tractable form, called statistical hypotheses. A correspondence, governed by the statistical model, exists between application-oriented notions in the research hypotheses (e.g., typical performance of a programming team under the disciplined methodology) and mathematical notions in the statistical hypotheses (e.g., expected value of a random variable defined over the population from which the disciplined teams are a representative sample). Generally speaking, only certain mathematical statements involving pairs of populations are statistically tractable, in the sense that standard statistical procedures are applicable. Statements that are not directly tractable may be broken down into tractable (sub)components whose results are properly recombined after having been decided individually.

In this study, the research hypotheses are concerned with directional differences among three programming environments. Since the corresponding mathematical statements are not directly tractable, they were broken down into the set of seven statistical hypotheses pairs shown below. The hypotheses pair

null: AI = AT = DT alternative: ¬(AI = AT = DT)

addresses the existence of an overall difference among the groups. However, due to the weak nondirectional alternative, it cannot indicate which groups are different or in what direction a difference lies. Standard statistical practice prescribes that a successful test for overall difference among three or more groups be followed by tests for pairwise differences. The hypotheses pairs

null: $AI = AT$ alternative: $AI \neq AT$ or $AI < AT$ or $AT < AI$
null: $AT = DT$ alternative: $AT \neq DT$ or $AT < DT$ or $DT < AT$
null: $AI = DT$ alternative: $AI \neq DT$ or $AI < DT$ or $DT < AI$

address the existence and direction of pairwise differences between groups. The results of these pairwise comparisions were used to explicate the overall comparison. Data collected for a set of experiments may often be legitimately reused to "simulate" other closely related experiments, by combining certain samples together and ignoring the original distinction(s) between them. It is meaningful, in the context of this study's experimental design, to compare any two groups pooled against the third since (1) AI and AT are both undisciplined, while DT is disciplined; (2) AT and DT are both teams, and AI is individuals; and (3) under the assumption that disciplined teams behave like individuals --which is part of the study's basic premise--, DT and AI can be pooled and compared with AT acting as a control group. The hypotheses pairs

null: $AI+AT = DT$ alternative: $AI+AT \neq DT$ or $AI+AT < DT$ or $DT < AI+AT$
null: $AT+DT = AI$ alternative: $AT+DT \neq AI$ or $AT+DT < AI$ or $AI < AT+DT$
null: $AI+DT = AT$ alternative: $AI+DT \neq AT$ or $AI+DT < AT$ or $AT < AI+DT$

address the existence and direction of such pooled differences. The results of these pooled comparisons were used to corrobate the overall and pairwise comparisons.

Thus, for any particular programming aspect, the research hypotheses pair corresponds to seven different pairs (null and alternative) of scientific hypotheses. The results of testing each set of seven hypotheses must be abstracted and organized into one statistical conclusion using the first research framework discussed in the next step.

Step 5: <u>Research Frameworks</u>

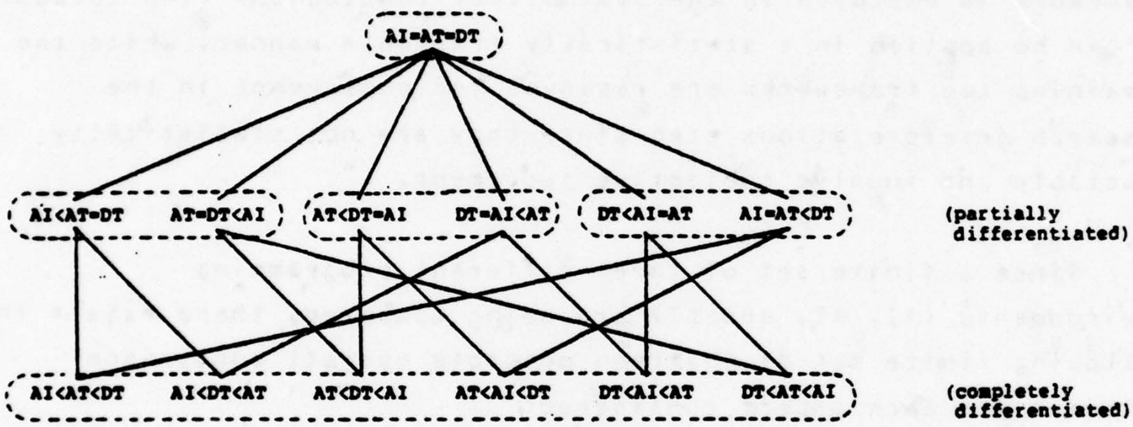
The research frameworks provide the necessary organizational basis for abstracting and conceptualizing the massive volume of statistical hypotheses (and statistical results that follow) into a smaller and more intellectually manageable set of conclusions. Three separate research frameworks have been chosen: (1) the framework of possible overall comparison outcomes for a given programming aspect, (2) the framework of dependencies and intuitive relationships among the various programming aspects considered, and (3) the framework of basic suppositions regarding expected effects of the experimental treatments on the comparison outcomes for the entire set of programming aspects. The first framework is employed in the statistical conclusions step because it can be applied in a statistically tractable manner, while the remaining two frameworks are reserved for employment in the research interpretations step since they are not statistically tractable and involve subjective judgement.

Since a finite set of three different programming environments (AI, AT, and DT) are being compared, there exists the following finite set of thirteen possible overall comparison outcomes for each aspect considered:

$$
\begin{array}{l}
AI = AT = DT \\
\left.\begin{array}{l} AI < AT = DT \\ AT = DT < AI \end{array}\right\} AI \neq AT = DT \\
\left.\begin{array}{l} AT < DT = AI \\ DT = AI < AT \end{array}\right\} AT \neq DT = AI \\
\left.\begin{array}{l} DT < AI = AT \\ AI = AT < DT \end{array}\right\} DT \neq AI = AT
\end{array}
\qquad
\left.\begin{array}{l}
AI < AT < DT \\
AI < DT < AT \\
AT < DT < AI \\
AT < AI < DT \\
DT < AI < AT \\
DT < AT < AI
\end{array}\right\} AI \neq AT \neq DT
$$

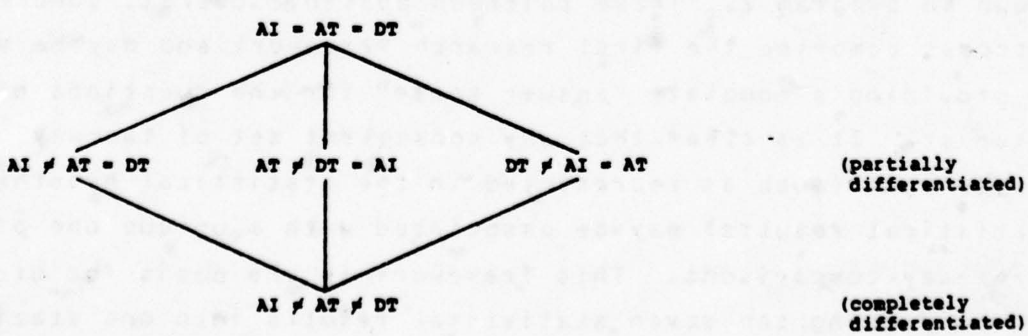
There is a hierarchical lattice of increasing separation and directionality among these possible overall comparison outcomes as shown in Diagram 2. These thirteen possible overall comparison outcomes comprise the first research framework and may be viewed as providing a complete "answer space" for the questions of interest. It is clear that any consistent set of two-way comparisons (such as represented in the statistical hypotheses or statistical results) may be associated with a unique one of these three-way comparisons. This framework is the basis for organizing and condensing the seven statistical results into one statistical conclusion for each programming aspect considered.

Diagram 2.1 Lattice of Possible Directional Outcomes for Three-way Comparison



N.B. The circles indicate which directional outcomes correspond to the same nondirectional outcome.

Diagram 2.2 Lattice of Possible Nondirectional Outcomes for Three-way Comparison



Since a large set of interrelated programming aspects are being examined, it would be desirable to summarize many of the "per aspect" hypotheses and results into statements which refer to several aspects simultaneously. For example, average number of statements per segment is one aspect directly dependent on two other aspects: number of segments and number of statements. Other interrelationships are more intuitive, less tractable, or only suspected, for example, the "trade-off" between global variables and formal parameters. A simple classification of the programming aspects into groups of intuitively related aspects at least provides a framework for jointly interpreting the corresponding statistical conclusions in light of the underlying issues by which the aspects themselves are related. The programming aspects considered in this study were classified according to a particular set of nine higher-level programming issues (such as data variable organization, for example); details are given in Section V, Interpretive Results. This second research framework is the basis for abstracting and interpreting what the study's findings indicate about these higher-level programming issues, as well as explicitly mentioning several individual relationships among the programming aspects and their conclusions.

Since the design of the experiments, the choice of treatment factors, etc., were at least partially motivated by certain general beliefs regarding software development (such as 'disciplined methodology reduces software development costs', for example), it should be possible to explicitly state what comparison outcomes among the experimental treatments were expected a priori for which programming aspects. A list of preplanned expectations (so-called "basic suppositions") for the outcomes of each aspect's experiment would provide a framework for evaluating how well the experimental findings as a whole support the underlying general beliefs (by comparing the actual outcomes with the basic suppositions across all the programming aspects). Such a list of basic suppositions was conceived prior to conducting the experiments, and it constitutes the third research framework; details are given in Section V, Interpretive Results.

This framework is the basis for interpreting the study's findings in terms of evidence in favor of the basic suppositions and general beliefs.

Step 6: Experimental Design

The experimental design is the plan or setup according to which the experiment is actually conducted or executed. It is based upon the statistical model, and deals with practical issues such as experimental units, treatment factors and levels, experimental local control, etc. The experimental design employed for this study has been discussed in considerable detail in Section II, Specifics.

Step 7: Collected Data

The pertinent data to carry out the experimental design was collected and processed to yield the information to which the statistical test procedures were applied. Some details of this execution phase are given in Section II, Specifics.

Step 8: Statistical Test Procedures

A statistical test procedure is a decision mechanism, founded upon general principles of mathematical probability and combinatorics and upon a specific statistical model (i.e., requiring certain assumptions), which is used to convert the statistical hypotheses together with the collected data into the statistical results. As dictated by the statistical model, the statistical tests used in the study were nonparametric tests of homogeneity of populations against shift alternatives for small samples. Nonparametric tests are slightly more conservative (in rejecting the null hypothesis) than their parametric counterparts; nonparametric tests generally use the ordinal ranks associated with a linear ordering of a set of scores, rather than the scores themselves, in their computational formulas. In particular, the standard Kruskal-Wallis H-test [Siegel 56; pp. 184-193] and

Mann-Whitney U-test [Siegel 56; pp. 116-127] were employed in the statistical results step. Ryan's Method of Adjusted Significance Levels [Kirk 68; pp. 97, 495-497], a standard procedure for controlling the experimentwise significance level when several tests are performed on the same scores as one experiment, was also employed in the statistical conclusions step.

The Kruskal-Wallis test is used in three-sample situations to test an X = Y = Z null hypothesis; its test statistic is computed as

H = 12*[(Rx*Rx/nx)+(Ry*Ry/ny)+(Rz*Rz/nz)]/[(n)*(n+1)] - 3*(n+1)

where Rx, Ry, and Rz are the respective sums of the ranks for scores from the X, Y, and Z samples; n equals nx+ny+nz; and nx, ny, and nz are the respective sample sizes. The Mann-Whitney test is used in two-sample situations to test an X = Y null hypothesis; its test statistic is computed as

U = min[nx*ny + nx*(nx+1)/2 - Rx ; ny*nx + ny*(ny+1)/2 - Ry]

where Rx, Ry, nx, and ny are defined as before.

For every statistical test, there exists a one-to-one mapping, usually given in statistical tables, between the test statistic --whose value is completely determined by the sample data scores-- and the critical level. The critical level $\hat{\alpha}$ [Conover 71; p. 81] is defined as the minimum significance level at which the statistical test procedure would allow the null hypothesis to be rejected (in favor of the alternative) for the given sample data. Thus critical level represents a concise standarized way to state the full result of any statistical test procedure. Two-tailed rejection regions are applied for tests involving nondirectional alternative hypotheses, and one-tailed rejection regions are applied for tests involving directional alternative hypotheses, so that the stated critical level always pertains directly to the stated alternative hypothesis. A decision to reject the null hypothesis and accept the alternative is mandated if the critical level is low enough to be tolerated; otherwise a decision to retain the null hypothesis is made.

The Ryan's procedure is used in situations involving multiple pairwise comparisons, in order to properly account for the fact that each pairwise test is made in conjunction with the others, using the same sample data. The individual critical levels $\hat{\alpha}$ obtained for each pairwise test in isolation are adjusted to proper experimentwise critical levels $\hat{\alpha}'$ via the formula

$$\hat{\alpha}' = [(r+1)*k/2] * \hat{\alpha}$$

where k is the total number of samples; and r is the number of (other) samples whose rank means fall between the rank means of the particular pair of samples being compared. A simple "minimax" step --taking the maximum of the several adjusted pairwise critical levels, plus the overall comparison critical level, which are all minimum significance levels-- completes the procedure, yielding a single critical level associated jointly with the overall and pairwise comparisons.

These tests and procedures apply straightforwardly when differences in location are considered. A slight modification makes them applicable for differences in dispersion: prior to ranking, each score value is simply replaced by its absolute deviation from the corresponding within-group sample median [Nemenyi et al. 77; pp. 266-270]. It should be noted that this modification results in only an approximate method for solving a tough statistical problem, namely, testing whether one population is more variable than another [Nemenyi et al. 77; pp. 279-283]. The modification is not strictly statistically "kosher" in the general case (it weakens the power of the test procedures and can yield inaccurate critical levels when testing for dispersion differences), but every other available method also has serious limitations. This method has been shown to possess reasonable accuracy as long as the underlying distributions are fairly symmetrical and it adapts easily to the study's three-way comparison situation.

Step 9: <u>Statistical Results</u>

A statistical result is essentially a decision reached by applying a statistical test procedure to the set of collected and refined data, regarding which one of the corresponding pair (null, alternative) of statistical hypotheses is indeed supported by that data. For each pair of statistical hypotheses, there is one statistical result consisting of four components: (1) the null hypothesis itself; (2) the alternative hypothesis itself; (3) the critical level, stated as a probability value between 0 and 1; and (4) a decision either to retain the null hypothesis or to reject it in favor of (i.e., accept) the alternative hypothesis.

By convention, the null hypothsis purports that no systematic difference appears to exist, and the alternative hypothesis purports that some systematic difference seems to exist. The critical level is associated with erroneously accepting the alternative hypothesis (i.e., claiming a systematic difference when none in fact exits). The decision to retain or reject is reached on the basis of some tolerable level of significance, with which the critical level is compared to see if it is low enough. In cases where a null hypothesis is rejected, the appropriate directional alternative hypothesis (if any) is used to indicate the direction of the systematic difference, as determined by direct observation from the sample medians in conjunction with a one-tailed test.

Conventional practice is to fix an arbitrary significance level (e.g., .05 or .01) in advance, to be used as the tolerable level; critical levels then serve only as stepping-stones toward reaching decisions and are not reported. For this partially exploratory study, it was deemed more appropriate to fix a tolerable level only for the purpose of a screening decision (which simply purges those results with intolerably high critical levels), and to carry the actual critical level along with each statistical result. This unconventional practice yields statistical results in a more meaningful and flexible form, since the significance or error risk of each result may be assessed individually, and results at other more stringent significance levels may be easily determined. Furthermore, the necessary information is retained for properly recombining multiple related results on an experimentwise basis in the statistical conclusions step.

The tolerable level of significance used throughout this study to sceen critical levels was fixed at under .20. Although fairly high for a confirmatory study, it is reasonable for a partially exploratory study, such as this one, seeking to discover even slight trends in the data. A critical level of .20 means that the odds of obtaining test scores exhibiting the same degree of difference, due to random chance fluctuations alone, are one in five.

As an example, the seven statistical results for location comparisons on the programming aspect STATEMENT TYPE COUNTS\IF are shown below. (N.B. The asterisks will be explained in Step 10.)

null hypothesis	alternative hypothesis	critical level	(screening) decision	
AI = AT = DT	-(AI = AT = DT)	.0630	reject	
AI = AT	AI < AT	.0465	reject	
AI = DT	AI ≠ DT	>.9999	retain	
AT = DT	DT < AT	.0111	reject	
AI+AT = DT	DT < AI+AT	.0884	reject	*
AI+DT = AT	AI+DT < AT	.0089	reject	
AT+DT = AI	AT+DT ≠ AI	.3352	retain	*

Observe that the stated decisions simply reflect the application of the .20 tolerable level to the stated critical levels. Results under more stringent levels of significance can be easily determined by simply applying a lower tolerable level to form the decisions; e.g., at the .05 significance level, only the AI < AT, DT < AT, and AI+DT < AT alternative hypotheses would be accepted; only the AI+DT < AT hypothesis would be accepted at the .01 level.

Step 10: <u>Statistical Conclusions</u>

The volume of statistical results are organized and condensed into statistical conclusions according to the prearranged research framework(s). A statistical concluson is an abstraction of several statistical results, but it retains the same statistical character, having been derived via statistically tractable methods and possessing an associated critical level.

Specifically, the first research framework mentioned above was employed to reduce the seven statistical results (with seven individual critical levels) for each programming aspect to a single statistical conclusion (with one overall critical level) for that aspect. The statement portion of a statistical conclusion is simply one of the thirteen possible overall comparison outcomes. Each overall comparison outcome is associated with a particular set of statistical results whose outcomes support the overall comparison outcome in a natural way. For example, the DT = AI < AT conclusion is associated with the following results:

reject AI = AT = DT in favor of ~(AI = AT = DT),
reject AI = AT in favor of AI < AT,
retain AI = DT,
reject AT = DT in favor of DT < AT, and
reject AI+DT = AT in favor of AI+DT < AT.

Since the other two comparisons (AI+AT versus AT, AT+DT versus AI) are in a sense orthogonal to the overall comparison outcome (DT = AI < AT), their results are considered irrelevant to this conclusion. The chart in Diagram 3 shows exactly which results are associated with each conclusion: the relevant comparisons, the null hypotheses to be retained, and the alternative hypotheses to be accepted. The other portion of a statistical conclusion is the critical level associated with erroneously accepting the statement portion. It is computed from the individual critical levels of certain germane results.

A simple deterministic algorithm, based on the chart in Diagram 3, was used to generate the statistical conclusions (and compute the overall critical level) automatically from the statistical results. For each programming aspect, the algorithm compared the actual results obtained for the seven statistical hypotheses pairs with the results associated with each conclusion, searching for a match. Ryan's procedure was used to properly combine the individual critical levels for the overall result and the relevant pairwise results, by adjusting them via the formula and then taking their maximum. The critical levels for the

Diagram 3. <u>Association Chart for Results and Conclusions</u>

The following chart specifies which statistical results are associated with each statistical conclusion. An asterisk indicates a comparison not relevant to that conclusion; the null hypothesis appears wherever it must be retained; and the alternative hypothesis to be accepted appears wherever the null hypothesis must be rejected. If a set of results do not satisfy the criteria associated with any of the non-null conclusions, then they are associated with the null conclusion by default.

conclusions:	results: AI=AT=DT	AI=AT	AI=DT	AT=DT	AI+AT=DT	AI+DT=AT	AT+DT=AI
AI = AT = DT				[default]			
AI < AT = DT	-(AI=AT=DT)	AI<AT	AI<DT	AT=DT	*	*	AI<AT+DT
AT = DT < AI	-(AI=AT=DT)	AT<AI	DT<AI	AT=DT	*	*	AT+DT<AI
AT < DT = AI	-(AI=AT=DT)	AT<AI	AI=DT	AT<DT	*	AT<AI+DT	*
DT = AI < AT	-(AI=AT=DT)	AI<AT	AI=DT	DT<AT	*	AI+DT<AT	*
DT < AI = AT	-(AI=AT=DT)	AI=AT	DT<AI	DT<AT	DT<AI+AT	*	*
AI = AT < DT	-(AI=AT=DT)	AI=AT	AI<DT	AT<DT	AI+AT<DT	*	*
AI < AT < DT	-(AI=AT=DT)	AI<AT	AI<DT	AT<DT	AI+AT<DT	*	AI<AT+DT
AI < DT < AT	-(AI=AT=DT)	AI<AT	AI<DT	DT<AT	*	AI+DT<AT	AI<AT+DT
AT < DT < AI	-(AI=AT=DT)	AT<AI	DT<AI	AT<DT	*	AT<AI+DT	AT+DT<AI
AT < AI < DT	-(AI=AT=DT)	AT<AI	AI<DT	AT<DT	AI+AT<DT	AT<AI+DT	*
DT < AI < AT	-(AI=AT=DT)	AI<AT	DT<AI	DT<AT	DT<AI+AT	AI+DT<AT	*
DT < AT < AI	-(AI=AT=DT)	AT<AI	DT<AI	DT<AT	DT<AI+AT	*	AT+DT<AI

relevant pooled results were factored in via a simple formula based on the multiplicative rule for the joint probability of independent events.

Continuing the example started in Step 9, the statistical results shown there for location comparisons on the STATEMENT TYPE COUNTS\IF aspect are reduced to the statistical conclusion DT = AI < AT with .0780 critical level overall. The five results not marked with an asterisk in Step 9 match the five results associated above with the DT = AI < AT outcome. (Note that the other two marked results represent comparisons which are irrelevant to this conclusion.) The .0465 and .0111 critical levels for the two pairwise differences are adjusted to .0697 and .0332, and the maximum of those adjusted values plus the .0630 overall difference critical level is .0697. The relevant pooled comparison critical level of .0089 is factored in by taking the complement of the products of the complements:

$$1 - [(1 - .0697)*(1 - .0089)] = .0780$$

Thus, the statistical conclusions are in one-to-one correspondence with the research hypotheses and provide concise answers on a "per aspect" basis to the questions of interest. Further details and complete listing of the statistical conclusions for this study are presented below in Section IV.

Step 11: Research Interpretations

The final step in the approach is to interpret the statistical conclusions in view of any remaining research framework(s), the researchers' intuitive and professional expectations, and the work of other researchers. These research interpretations provide the opportunity to augment the objective findings of the study with the researcher's own subjective judgments and interpretations. The second and third research frameworks mentioned above --namely, the intuitive relationships among the various programming aspects and the basic suppositions governing their expected outcomes-- were considered important.

However these particular research frameworks can only be utilized for the research interpretations, since they are not amenable to rigorous manipulation. Nonetheless, within these frameworks which are based upon intuitive understanding about the programming aspects and software development environments under consideration, the study bears some of its most interesting results and implications. Complete details and discussion of the research interpretations of this study appear in Section V.

IV. Objective Results

This section reports the objective results of the study, namely, the statistical conclusions for each programming aspect considered. The tone of discussion here is purposely somewhat disinterested and analytical, in keeping with the empirical and statistical character of these conclusions. All interpretive discussion is deferred to Section V.

Each statistical conclusion is expressed in the concise form of a three-way comparison outcome "equation." It states any observed differences, and the directions thereof, among the programming environments represented by the three groups examined in the study: ad hoc individuals (AI), ad hoc teams (AT), and disciplined teams (DT). The equality AI = AT = DT expresses the null conclusion that there is no systematic difference among the groups. An inequality, e.g., AI < AT = DT or DT < AI < AT, expresses a non-null (or alternative) conclusion that there are certain systematic difference(s) among the groups in stated direction(s). A critical level (or risk) value is also associated with each non-null (or alternative) conclusion, indicating its individual reliability. This value is the probability of having erroneously rejected the null conclusion in favor of the alternative; it also provides a relative index of how pronounced the differences were in the sample data.

The remainder of this section consists of (a) presenting the full set of conclusions, (b) evaluating their impact as a whole, (c) exposing a "relaxed differentiation" view of the conclusions, (d) exposing a "directionless" view of the conclusions, and (e) individually highlighting a few of the more noteworthy conclusions.

Presentation

Instances of non-null (or alternative) conclusions indicating some distinction among the groups on the basis of a particular programming aspect are listed by outcome in Tables 2.1 (for location comparisons) and 2.2 (for dispersion comparisons). A complete itemization of these distinctions, in English prose form, appears in Appendix 2. The complete set of statistical conclusions for both location and dispersion comparisons appears in Table 3 arranged by programming aspect.

Examination of Table 3 immediately demonstrates that a large number of the programming aspects considered in this study, especially product aspects, failed to show any distinction between the groups. This low "yield" is not surprising, especially among product aspects, and may be attributed to the partially exploratory nature of the study, the small sample sizes, and the general coarseness of many of the aspects considered. The issue of these null outcome occurrences and their significance is treated more thoroughly in the next subsection, Impact Evaluation.

It is worth noting, however, that several of the null conclusions may indicate characteristics inherent to the application itself. As one example, the basic symbol-table/scan/parse/code-generation nature of a compiler strongly influences the way the system is modularized and thus practically determines the number of modules in the final product (give or take some occassional slight variation due to other design decisions).

Impact Evaluation

These statistical conclusions have a certain objective character --since they are statistically inferred from empirical data-- and their collective impact may be objectively evaluated according to the following statistical principle [Tukey 69; p. 84-85]. Whenever a series of statistical tests (or experiments) are made, all at a fixed level of significance (for example, .10), a corresponding percentage (in the example, 10%) of the tests are expected a priori to reject the null hypothesis in the complete absence of any true effect (i.e., due to chance alone). This

Table 2.1 Non-Null Conclusions, for Location Comparisons, arranged by outcome

comparison outcome	critical level	*	programming aspect
AI < AT = DT		8	
	0.0634		SEGMENTS
	0.0693		DATA VARIABLES
	0.1476		DATA VARIABLE SCOPE COUNTS \ GLOBAL
	0.1614		DATA VARIABLE SCOPE COUNTS \ GLOBAL \ MODIFIED
	0.1271		DATA VARIABLE SCOPE COUNTS \ NONGLOBAL \ PARAMETER
	0.1507		DATA VARIABLE SCOPE PERCENTAGES \ NONGLOBAL \ PARAMETER
	0.1748		AVERAGE NONGLOBAL VARIABLES PER SEGMENT \ PARAMETER
	0.1227		(SEG,GLOBAL) POSSIBLE USAGE PAIRS
AT = DT < AI		5	
	0.1706		AVERAGE STATEMENTS PER SEGMENT
	0.1699		AVG INVOCATIONS PER (CALLING) SEGMENT \ NONINTRINSIC
	0.1699		AVG INVOCATIONS PER (CALLED) SEGMENT
	0.1936		AVG INVOCATIONS PER (CALLED) SEGMENT \ FUNCTION
	0.1090		DATA VARIABLE SCOPE PERCENTAGES \ NONGLOBAL \ LOCAL
AT < DT = AI		1	
	0.1546		(SEG,GLOBAL) USAGE RELATIVE PERCENTAGES \ NONENTRY \ UNMODIFIED
DT = AI < AT		8	
	0.0780		STATEMENT TYPE COUNTS \ IF
	0.1732		STATEMENT TYPE COUNTS \ (PROC)CALL \ INTRINSIC
	0.0860		STATEMENT TYPE COUNTS \ RETURN
	0.1069		STATEMENT TYPE PERCENTAGES \ IF
	0.1468		DECISIONS
	0.1732		INVOCATIONS \ PROCEDURE \ INTRINSIC
	0.0435		INVOCATIONS \ INTRINSIC
	0.1861		(SEG,GLOBAL,SEG) DATA BINDINGS \ POSSIBLE
DT < AI = AT		8	
	0.0036		COMPUTER JOB STEPS
	0.0223		COMPUTER JOB STEPS \ MODULE COMPILATIONS
	0.0110		COMPUTER JOB STEPS \ MODULE COMPILATIONS \ UNIQUE
	0.0221		COMPUTER JOB STEPS \ PROGRAM EXECUTIONS
	0.1445		COMPUTER JOB STEPS \ MISCELLANEOUS
	0.0037		ESSENTIAL JOB STEPS
	0.0883		AVERAGE UNIQUE COMPILATIONS PER MODULE
	0.1180		MAX UNIQUE COMPILATIONS F.A.O. MODULE
AI = AT < DT		0	
AI < AT < DT		0	
AI < DT < AT		1	
	0.1194		LINES
AT < DT < AI		2	
	0.1173		(SEG,GLOBAL) USAGE RELATIVE PERCENTAGES \ ENTRY
	0.1232		(SEG,GLOBAL) USAGE RELATIVE PERCENTAGES \ ENTRY \ MODIFIED
AT < AI < DT		0	
DT < AI < AT		1	
	0.1849		PROGRAM CHANGES
DT < AT < AI		0	

* this column records the frequency of occurrence for each comparison outcome

Table 2.2 Non-Null Conclusions, for Dispersion Comparisons, arranged by outcome

comparison outcome	critical level	*	programming aspect
AI < AT = DT		6	
	0.0199		DATA VARIABLE SCOPE COUNTS \ NONGLOBAL \ PARAMETER \ REFERENCE
	0.1529		DATA VARIABLE SCOPE PERCENTAGES \ NONGLOBAL \ PARAMETER \ REFERENCE
	0.1606		PARAMETER PASSAGE TYPE PERCENTAGES \ VALUE
	0.1606		PARAMETER PASSAGE TYPE PERCENTAGES \ REFERENCE
	0.0786		(SEG,GLOBAL) POSSIBLE USAGE PAIRS \ NONENTRY
	0.1963		(SEG,GLOBAL,SEG) DATA BINDINGS \ ACTUAL \ INDEPENDENT
AT = DT < AI		3	
	0.0775		COMPUTER JOB STEPS \ MISCELLANEOUS
	0.0206		INVOCATIONS
	0.0510		INVOCATIONS \ NONINTRINSIC
AT < DT = AI		3	
	0.1954		STATEMENTS
	0.1411		AVG INVOCATIONS PER (CALLED) SEGMENT \ FUNCTION
	0.1061		(SEG,GLOBAL) ACTUAL USAGE PAIRS \ MODIFIED
DT = AI < AT		5	
	0.0219		AVERAGE SEGMENTS PER MODULE
	0.0401		STATEMENT TYPE PERCENTAGES \ RETURN
	0.1100		AVERAGE GLOBAL VARIABLES PER MODULE \ MODIFIED
	0.0510		(SEG,GLOBAL) POSSIBLE USAGE PAIRS \ NONENTRY \ MODIFIED
	0.1529		(SEG,GLOBAL,SEG) DATA BINDINGS \ POSSIBLE
DT < AI = AT		6	
	0.0325		STATEMENT TYPE COUNTS \ (PROC)CALL
	0.1862		STATEMENT TYPE COUNTS \ (PROC)CALL \ NONINTRINSIC
	0.0325		INVOCATIONS \ PROCEDURE
	0.1862		INVOCATIONS \ PROCEDURE \ NONINTRINSIC
	0.0653		AVG INVOCATIONS PER (CALLING) SEGMENT \ PROCEDURE \ INTRINSIC
	0.0218		DATA VARIABLE SCOPE PERCENTAGES \ GLOBAL \ NONENTRY \ MODIFIED
AI = AT < DT		7	
	0.1061		AVERAGE TOKENS PER STATEMENT
	0.1241		DATA VARIABLE SCOPE COUNTS \ GLOBAL
	0.1061		DATA VARIABLE SCOPE COUNTS \ NONGLOBAL \ PARAMETER
	0.0750		DATA VARIABLE SCOPE PERCENTAGES \ GLOBAL
	0.0750		DATA VARIABLE SCOPE PERCENTAGES \ NONGLOBAL
	0.0557		DATA VARIABLE SCOPE PERCENTAGES \ NONGLOBAL \ PARAMETER
	0.0943		DATA VARIABLE SCOPE PERCENTAGES \ NONGLOBAL \ PARAMETER \ VALUE
AI < AT < DT		0	
AI < DT < AT		2	
	0.0523		(SEG,GLOBAL) POSSIBLE USAGE PAIRS
	0.1727		(SEG,GLOBAL) POSSIBLE USAGE PAIRS \ NONENTRY \ UNMODIFIED
AT < DT < AI		0	
AT < AI < DT		0	
DT < AI < AT		2	
	0.0514		MAX UNIQUF COMPILATIONS F.A.O. MODULE
	0.1798		STATEMENT TYPE COUNTS \ RETURN
DT < AT < AI		0	

* this column records the frequency of occurrence for each comparison outcome

Table 3. Statistical Conclusions

N.B. A simple pair of equal signs (= =) appears in place of the null outcome AI = AT = DT in order to avoid cluttering the table excessively.

programming aspect	location comparison outcome	location critical level	dispersion comparison outcome	dispersion critical level
development process aspects :				
COMPUTER JOB STEPS	DT < AI = AT	0.0036	= =	
MODULE COMPILATIONS	DT < AI = AT	0.0223	= =	
UNIQUE	DT < AI = AT	0.0110	= =	
IDENTICAL	= =		= =	
PROGRAM EXECUTIONS	DT < AI = AT	0.0221	= =	
MISCELLANEOUS	DT < AI = AT	0.1445	AT = DT < AI	0.0775
ESSENTIAL JOB STEPS	DT < AI = AT	0.0037	= =	
AVERAGE UNIQUE COMPILATIONS PER MODULE	DT < AI = AT	0.0883	= =	
MAX UNIQUE COMPILATIONS F.A.O. MODULE	DT < AI = AT	0.1180	DT < AI < AT	0.0514
PROGRAM CHANGES	DT < AI < AT	0.1848	= =	
final product aspects :				
MODULES	= =		= =	
SEGMENTS	AI < AT = DT	0.0634	= =	
SEGMENT TYPE COUNTS :				
FUNCTION	= =		= =	
PROCEDURE	= =		= =	
SEGMENT TYPE PERCENTAGES :				
FUNCTION	= =		= =	
PROCEDURE	= =		= =	
AVERAGE SEGMENTS PER MODULE	= =		DT = AI < AT	0.0218
LINES	AI < DT < AT	0.1194	= =	
STATEMENTS	= =		AT < DT = AI	0.1954
STATEMENT TYPE COUNTS :				
:=	= =		= =	
IF	DT = AI < AT	0.0780	= =	
CASE	= =		= =	
WHILE	= =		= =	
EXIT	= =		= =	
(PROC)CALL	= =		DT < AI = AT	0.0325
NONINTRINSIC	= =		DT < AI = AT	0.1862
INTRINSIC	DT = AI < AT	0.1732	= =	
RETURN	DT = AI < AT	0.0860	DT < AI < AT	0.1398
STATEMENT TYPE PERCENTAGES :				
:=	= =		= =	
IF	DT = AI < AT	0.1069	= =	
CASE	= =		= =	
WHILE	= =		= =	
EXIT	= =		= =	
(PROC)CALL	= =		= =	
NONINTRINSIC	= =		= =	
INTRINSIC	= =		= =	
RETURN	= =		DT = AI < AT	0.0401
AVERAGE STATEMENTS PER SEGMENT	AT = DT < AI	0.1706	= =	
AVERAGE STATEMENT NESTING LEVEL	= =		= =	
DECISIONS	DT = AI < AT	0.1468	= =	

FUNCTION CALLS	= =		= =	
NONINTRINSIC	= =		= =	
INTRINSIC	= =		= =	
TOKENS	= =		= =	
AVERAGE TOKENS PER STATEMENT	= =		AI = AT < DT	0.1061
INVOCATIONS	= =		AT = DT < AI	0.0206
FUNCTION	= =		= =	
NONINTRINSIC	= =		= =	
INTRINSIC	= =		= =	
PROCEDURE	= =		DT < AI = AT	0.0325
NONINTRINSIC	= =		DT < AI = AT	0.1862
INTRINSIC	DT = AI < AT	0.1732	= =	
NONINTRINSIC	= =		AT = DT < AI	0.0510
INTRINSIC	DT = AI < AT	0.0435	= =	
AVG INVOCATIONS PER (CALLING) SEGMENT	= =		= =	
FUNCTION	= =		= =	
NONINTRINSIC	= =		= =	
INTRINSIC	= =		= =	
PROCEDURE	= =		= =	
NONINTRINSIC	= =		= =	
INTRINSIC	= =		DT < AI = AT	0.0653
NONINTRINSIC	AT = DT < AI	0.1699	= =	
INTRINSIC	= =		= =	
AVG INVOCATIONS PER (CALLED) SEGMENT	AT = DT < AI	0.1699	= =	
FUNCTION	AT = DT < AI	0.1936	AT < DT = AI	0.1411
PROCEDURE	= =		= =	
DATA VARIABLES	AI < AT = DT	0.0698	= =	
DATA VARIABLE SCOPE COUNTS :				
GLOBAL	AI < AT = DT	0.1476	AI = AT < DT	0.1241
ENTRY	= =		= =	
MODIFIED	= =		= =	
UNMODIFIED	= =		= =	
NONENTRY	= =		= =	
MODIFIED	= =		= =	
UNMODIFIED	= =		= =	
MODIFIED	AI < AT = DT	0.1614	= =	
UNMODIFIED	= =		= =	
NONGLOBAL	= =		= =	
PARAMETER	AI < AT = DT	0.1271	AI = AT < DT	0.1061
VALUE	= =		= =	
REFERENCE	= =		AI < AT = DT	0.0199
LOCAL	= =		= =	
DATA VARIABLE SCOPE PERCENTAGES :				
GLOBAL	= =		AI = AT < DT	0.0750
ENTRY	= =		= =	
MODIFIED	= =		= =	
UNMODIFIED	= =		= =	
NONENTRY	= =		= =	
MODIFIED	= =		DT < AI = AT	0.0218
UNMODIFIED	= =		= =	
MODIFIED	= =		= =	
UNMODIFIED	= =		= =	
NONGLOBAL	= =		AI = AT < DT	0.0750
PARAMETER	AI < AT = DT	0.1507	AI = AT < DT	0.0557
VALUE	= =		AI = AT < DT	0.0943
REFERENCE	= =		AI < AT = DT	0.1529
LOCAL	AT = DT < AI	0.1090	= =	
AVERAGE GLOBAL VARIABLES PER MODULE	= =		= =	
ENTRY	= =		= =	
NONENTRY	= =		= =	
MODIFIED	= =		DT = AI < AT	0.1100
UNMODIFIED	= =		= =	
AVERAGE NONGLOBAL VARIABLES PER SEGMENT	= =		= =	
PARAMETER	AI < AT = DT	0.1748	= =	
LOCAL	= =		= =	

PARAMETER PASSAGE TYPE PERCENTAGES :				
VALUE	= =		AI < AT = DT	0.1606
REFERENCE	= =		AI < AT = DT	0.1606
(SEG,GLOBAL) ACTUAL USAGE PAIRS	= =		= =	
ENTRY	= =		= =	
MODIFIED	= =		= =	
UNMODIFIED	= =		= =	
NONENTRY	= =		= =	
MODIFIED	= =		= =	
UNMODIFIED	= =		= =	
MODIFIED	= =		AT < DT = AI	0.1061
UNMODIFIED	= =		= =	
(SEG,GLOBAL) POSSIBLE USAGE PAIRS	AI < AT = DT	0.1227	AI < DT < AT	0.0523
ENTRY	= =		= =	
MODIFIED	= =		= =	
UNMODIFIED	= =		= =	
NONENTRY	= =		AI < AT = DT	0.0786
MODIFIED	= =		DT = AI < AT	0.0510
UNMODIFIED	= =		AI < DT < AT	0.1727
MODIFIED	= =		= =	
UNMODIFIED	= =		= =	
(SEG,GLOBAL) USAGE RELATIVE PERCENTAGES	= =		= =	
ENTRY	AT < DT < AI	0.1173	= =	
MODIFIED	AT < DT < AI	0.1232	= =	
UNMODIFIED	= =		= =	
NONENTRY	= =		= =	
MODIFIED	= =		= =	
UNMODIFIED	AT < DT = AI	0.1546	= =	
MODIFIED	= =		= =	
UNMODIFIED	= =		= =	
(SEG,GLOBAL,SEG) DATA BINDINGS :				
ACTUAL	= =		= =	
SUBFUNCTIONAL	= =		= =	
INDEPENDENT	= =		AI < AT = DT	0.1963
POSSIBLE	DT = AI < AT	0.1861	DT = AI < AT	0.1529
RELATIVE PERCENTAGE	= =		= =	

expected rejection percentage provides a comparative index of the true impact of the test results as a whole (in the example, a 25% actual rejection percentage would indicate that a truely significant effect, other than chance alone, was operative).

The point here may be illustrated in terms of simple coin-tossing experiments. The nature of statistics itself dictates that, out of a series of 100 separate statistical tests of a hypothetically fair coin at the .05 significance level, roughly 5 of those tests would nonetheless indicate that the coin was biased; if only 6 out of 100 tests of a real coin indicate bias at the .05 level, those six results have very little impact since the coin is behaving rather unbiasedly over the full set of tests.

This same "multiplicity" principle applies to the statistical conclusions of the study, since they represent the outcomes of a series of separate tests and were assumed in the statistical model to be separate experiments. It is appropriate to evaluate the location and dispersion results separately, since they reflect two separate issues (expectency and predictability) of software development behavior. Similarly, it is also appropriate to evaluate the process and product results separately. Finally, it is only fair to evaluate the "confirmatory" aspects as a distinct subset of all aspects examined, since they alone had been honestly considered prior to collecting and analyzing the data.

The details of this impact evaluation for the study's objective results, broken down into the appropriate categories identified above, are presented in the following table. The evaluation was performed at the α=.20 significance level used for screening purposes, hence the expected rejection percentage for any category was 20%. For each category of aspects, the table gives the number of (nonredundant) programming aspects, the expected (rounded to whole numbers) and actual numbers of rejections (of the null conclusion in favor of a directional alternative), and the expected and actual rejection percentages.

An asterisk marks those categories demonstrating noticable statistical impact (i.e., actual rejection percentage well above expected rejection percentage).

category	number of aspects	expect. num. of reject.	actual num. of reject.	expect. reject. percent	actual reject. percent	
location	130	26	32	20.0	24.6	
process	10	2	9	20.0	90.0	*
confirmatory only	6	1	6	20.0	100.0	*
product	120	24	23	20.0	19.2	
confirmatory only	29	6	12	20.0	41.3	*
confimatory only	35	7	18	20.0	51.4	*
dispersion	130	26	32	20.0	24.6	
process	10	2	2	20.0	20.0	
confirmatory only	6	1	0	20.0	0.0	
product	120	24	30	20.0	25.0	
confirmatory only	29	6	9	20.0	31.0	*
confirmatory only	35	7	9	20.0	25.7	

The table shows that the location results, dealing with the expectency of software development behavior, do have statistical impact in several subcategories. Process aspects have more impact than product aspects on the whole, but when tempered by consideration of the distinction between "confirmatory" and "exploratory" aspects, the study's location reults bear strong statistical impact for both process and product. They are better explained as the consequence of some true effect related to the experimental treatments, rather than as a random phenomenon.

It is also clear from the table that the dispersion results, dealing with the predictability of software development behavior, have little statistical impact in general. This is due primarily to the diminished power of statistical procedures used to test for dispersion differences, compounded by the small sample sizes involved and the coarseness of many of the programming aspects themselves. The lack of strong statistical impact in this area of the study does not mean that the dispersion issue is unimportant or undeserving of research attention, but rather that it is "a tougher nut to crack" than the location issue. The study's dispersion results are still worth persuing, however, as possible hints of where differences might exist, provided this disclaimer regarding their impact is heeded.

A Relaxed Differentiation View

As described in Section III, the research framework of possible three-way comparison outcomes provided the basis for converting the statistical results into the statistical conclusions. This framework has two inherent structural characteristics that may be exploited to make additional observations regarding the statistical conclusions. These structural characteristics and the supplemental views of the conclusions that they afford are described here and in the next subsection.

Specifically, the first structural characteristic is that each completely differentiated outcome is related to a specific pair of partially differentiated outcomes, as shown in the lattice of Diagram 2.1. For example, AI < AT < DT, a completely differentiated outcome, naturally weakens to either AI < AT = DT or AI = AT < DT, two partially differentiated outcomes.

Each completely differentiated outcome consists of three pairwise differences (AI < AT, AT < DT, AI < DT in the example), while each partially differentiated outcome consists of only two pairwise differences plus one pairwise equality (AI < DT, AI < AT, AT = DT and AI < DT, AT < DT, AI = AT in the example). The "outer" difference of the completely differentiated outcome (AI < DT in the example) is common to both partially differentiated outcomes, while each partially differentiated outcome focuses attention on one of the two "inner" differences (AI < AT and AT < DT in the example) to the exclusion of the other "inner" difference which is "relaxed" to an equality. Within a statistical environment or model which places a premium on claiming differences instead of equalities, a partially differentiated outcome is a safer statement, containing less error-prone information than a completely differentiated outcome. Since these outcomes represent statistical conclusions, the same data scores which support a completely differentiated outcome at a certain critical level also support each of the two related partially differentiated outcomes at lower critical levels.

Thus, every completely differentiated conclusion may also be considered as two (more significant) partially differentiated conclusions, each of these three conclusions having equal and complete statistical legitimacy. The "outer" difference of a completely differentiated conclusion is, of course, stronger than either of its two "inner" differences; but the strengths of the two "inner" differences (relative to each other) will vary in accordance with the data scores and indeed are reflected in the significance levels of the two corresponding partially differentiated conclusions (relative to each other). Tables 4.1 and 4.2 give the details of this "relaxed differentiation" analysis for each of the completely differentiated conclusions found in the study, and an English paraphrase appears in Appendix 3. All of the partially differentiated conclusions listed in these tables should be added to those presented in Tables 2 and 3; they deserve full consideration in any analysis or interpretation of the study's findings. However, in the case that one of a partially differentiated pair is noticeably stronger than the other, it is fair to consider only the stronger one for the purpose of analysis or interpretation dealing primarily with partially differentiated outcomes, since the study is mainly concerned with the most pronounced difference afforded by each aspect's data scores.

A Directionless View

The second structural characteristic of the possible outcome framework is that the outcomes may be classified into another closely related set of directionless outcomes, as shown in the lattice of Diagram 2.2. For example, $AI < AT = DT$ and $AT = DT < AI$, two directional partially differentiated outcomes, both correspond to $AI \neq AT = DT$, a nondirectional partially differentiated outcome. All six of the directional completely differentiated outcomes correspond to the single nondirectional completely differentiated outcome $AI \neq AT \neq DT$.

Table 4.1 Relaxed Differentiation for Location Comparisons

programming aspect	completely differentiated conclusion: comparison outcome	critical level	partially differentiated conclusions: comparison outcome	critical level
PROGRAM CHANGES	DT < AI < AT	0.1848	DT < AI = AT DT = AI < AT	0.0037 0.1846
LINES	AI < DT < AT	0.1194	DT = AI < AT AI < AT = DT	0.0617 0.1132
(SEG,GLOBAL) USAGE RELATIVE PERCENTAGES \ ENTRY	AT < DT < AI	0.1173	AT < DT = AI AT = DT < AI	0.0826 0.1111
(SEG,GLOBAL) USAGE RELATIVE PERCENTAGES \ ENTRY \ MODIFIED	AT < DT < AI	0.1232	AT < DT = AI AT = DT < AI	0.1132 0.1132

Table 4.2 Relaxed Differentiation for Dispersion Comparisons

programming aspect	completely differentiated conclusion: comparison outcome	critical level	partially differentiated conclusions: comparison outcome	critical level
MAX UNIQUE COMPILATIONS F.A.O. MODULE	DT < AI < AT	0.0514	DT < AI = AT DT = AI < AT	0.0036 0.0511
STATEMENT TYPE COUNTS \ RETURN	DT < AI < AT	0.1398	DT = AI < AT DT < AI = AT	0.0035 0.1395
(SEG,GLOBAL) POSSIBLE USAGE PAIRS	AI < DT < AT	0.0523	AI < AT = DT DT = AI < AT	0.0207 0.0511
(SEG,GLOBAL) POSSIBLE USAGE PAIRS \ NONENTRY \ UNMODIFIED	AI < DT < AT	0.1727	AI < AT = DT DT = AI < AT	0.1167 0.1561

By emphasizing only the observed distinctions between the groups, these directionless outcome categories focus attention on the original research issue of how observable programming aspects reflect differences among the three programming environments. In particular, there are three nondirectional partially differentiated outcomes (each of the form "one group different from the other two which are similar"), and it is noteworthy to observe just what set of programming aspects supports each of these basic distinctions. It is fairly easy to coalesce the directional distinctions from Table 2 into the directionless categories by eye, but a complete itemization of directionless distinctions is provided in Appendix 4. It is interesting to note that, for location comparisons, the directionless distinctions segregate cleanly along the process versus product dicotomy line: all of the product distinctions fall into the AI ≠ AT = DT and AT ≠ DT = AI directionless categories, while all of the process distinction fall into the DT ≠ AI = AT directionless category.

Individual Highlights

The purpose of this concluding subsection is simply to draw attention to what seem to be the "top ten" (or so) most noteworthy conclusions from among the study's objective results. These conclusions are interesting individually, either because the programming aspect itself has general appeal or because the difference in behavior expectency or predictability is well pronounced (as indicated by a low critical significance level) in the experimental sample data.

Noteworthy location distinctions are mentioned below.

1. According to the DT < AI = AT outcome on the COMPUTER JOB STEPS aspect, the disciplined teams used very noticeably fewer computer job steps (i.e., module compilations, program executions, or miscellaneous job steps) than both the ad hoc individuals and the ad hoc teams.
2. This same difference was apparent in the total number of module compilations, the number of unique (i.e., not an

identical recompilation of a previously compiled module) module compilations, the number of program executions, and the number of essential job steps (i.e., unique module compilations plus program executions), according to the DT < AI = AT outcomes on the COMPUTER JOB STEPS\MODULE COMPILATIONS, COMPUTER JOB STEPS\MODULE COMPILATIONS\UNIQUE, COMPUTER JOB STEPS\PROGRAM EXECUTIONS, and ESSENTIAL JOB STEPS aspects, respectively.

3. According to the DT < AI = AT outcome on the PROGRAM CHANGES aspect, the disciplined teams required fewer textual revisions to build and debug the software than the ad hoc individuals and the ad hoc teams.
4. There was a definite trend for the ad hoc individuals to have produced fewer total symbolic lines (includes comments, compiler directives, statements, declarations, etc.) than the disciplined teams who produced fewer than the ad hoc teams, according to the AI < DT < AT outcome on the LINES aspect.
5. According to the AI < AT = DT outcome on the SEGMENTS aspect, the ad hoc individuals organized their software into noticeably fewer routines (i.e., functions or procedures) than either the ad hoc teams or the disciplined teams.
6. The ad hoc individuals displayed a trend toward having a greater number of statements per routine than did either the ad hoc teams or the disciplined teams, according to the AT = DT < AI outcome on the AVERAGE STATEMENTS PER SEGMENT aspect.
7. According to the DT = AI < AT outcomes on the STATEMENT TYPE COUNTS\IF and STATEMENT TYPE PERCENTAGE\IF aspects, both the ad hoc individuals and the disciplined teams coded noticeably fewer IF statements than the ad hoc teams, in terms of both total number and percentage of total statements.
8. According to the DT = AI < AT outcome on the DECISIONS aspect, both the ad hoc individuals and the disciplined teams tended to code fewer decisions (i.e., IF, WHILE, or CASE statements) than the ad hoc teams.
9. Both the ad hoc teams and the disciplined teams declared a noticeably larger number of data variables (i.e., scalars or

arrays of scalars) than the ad hoc individuals, according to the AI < AT = DT outcome on the DATA VARIABLES aspect.

10. According to the AT = DT < AI outcome on the DATA VARIABLE SCOPE PERCENTAGES\NONGLOBAL\LOCAL aspect, the ad hoc individuals had a larger percentage of local variables compared to the total number of declared data variables than either the ad hoc teams or the disciplined teams.

11. There was a slight trend for both the ad hoc individuals and the disciplined teams to have fewer potential data bindings [Stevens, Myers, and Constantine 74] (i.e., occurrences of the situation where a global variable could be modified by one segment and accessed by another due to the software's modularization) than the ad hoc teams, according to the DT = AI < AT outcome on the (SEG,GLOBAL,SEG) DATA BINDINGS\ POSSIBLE aspect.

Noteworthy <u>dispersion</u> distinctions are mentioned below.

1. There was a noticeable difference in variability, with the disciplined teams less than the ad hoc individuals less than the ad hoc teams, in the maximum number of unique compilations for any one module, according to the DT < AI < AT outcome on the MAX UNIQUE COMPILATIONS F.A.O. MODULE aspect.

2. The ad hoc individuals exhibited noticeably greater variation than either the ad hoc teams or the disciplined teams in the number of miscellaneous job steps (i.e., auxiliary compilations or executions of something other than the final software project), according to the AT = DT < AI outcome on the COMPUTER JOB STEPS\MISCELLANEOUS aspect.

3. According to the DT = AI < AT outcome on the AVERAGE SEGMENTS PER MODULE aspect, the ad hoc individuals and the disciplined teams both exhibited noticeably less variation in the average number of routines per module than the ad hoc teams.

4. According to the DT = AI < AT outcomes on the STATEMENT TYPE COUNTS\RETURN and STATEMENT TYPE PERCENTAGES\RETURN aspects, the ad hoc teams showed rather noticeably greater variability in the number (both raw count and normalized percentage) of

RETURN statements coded than both the disciplined teams and the ad hoc individuals.

5. In the number of calls to programmer-defined routines, the ad hoc individuals displayed noticeably greater variation than both the ad hoc teams and the disciplined teams, according to the AT = DT < AI outcome on the INVOCATIONS\NONINTRINSIC aspect.
6. According to the DT < AI = AT outcome on the DATA VARIABLES SCOPE PERCENTAGES\GLOBAL\NONENTRY\MODIFIED aspect, the disciplined teams displayed noticeably smaller variation than either the ad hoc individuals or the ad hoc teams in the percentage of commonplace (i.e., ordinary scope and modified during execution) global variables compared to the total number of data variables declared.
7. The ad hoc individuals displayed noticeably less variation in the number of formal parameters passed by reference than both the ad hoc teams and the disciplined teams, according to the AI < AT = DT outcome on the DATA VARIABLE SCOPE COUNTS\ NONGLOBAL\PARAMETER\REFERENCE aspect.
8. According to the AI < DT < AT outcome on the (SEG,GLOBAL) POSSIBLE USAGE PAIRS aspect, there was a noticeable difference in variability, with the ad hoc individuals less than the disciplined teams less than the ad hoc teams, for the total number of possible segment-global usage pairs (i.e., occurrences of the situation where a global variable could be modified or accessed by a segment).
9. According to the DT = AI < AT outcome on the (SEG,GLOBAL,SEG) DATA BINDINGS\POSSIBLE aspect, the ad hoc teams tended toward greater variability than either the ad hoc individuals or the disciplined teams in the number of potential data bindings.

V. Interpretive Results

This section reports the interpretive results of the study, namely the research interpretations based on the conclusions presented in Section IV. The tone of discussion here is purposely somewhat subjective and opinionated, since the study's most important results are derived from interpreting the experiment's immediate findings in view of the study's overall goals. These interpretations also express the researchers' own estimation of the study's implications and general import according to their professional intuitions about programming and software.

The interpretations presented here are neither exhaustive nor unique. They only touch upon certain overall issues and generally avoid attaching meaning to or giving explanation for individual aspects or outcomes. It is anticipated that the reader and other researchers might formulate additional or alternative interpretations of the study's factual findings, using their own intuitive judgments.

Two distinct sets of research interpretations are discussed in the remainder of this section. The first set states general trends in the conclusions according to the basic suppositions of the study. The second set states general trends in the conclusions based on classifications which reflect certain abstract programming notions (e.g., cost, modularity, data organizations, etc.).

According to Basic Suppositions:

The study's basic suppositions are a set of the simplest a priori expectations (or "hypotheses") for the outcomes of location and dispersion comparisons on process and product aspects. They are stated in the following table:

Basic Suppositions	on Location and Dispersion Comparisons
for Process Aspects	DT < AI = AT
for Product Aspects	DT = AI < AT or AT < DT = AI

The basic suppositions are founded upon certain general beliefs regarding software development, which had been formulated by the researchers prior to conducting the experiment. The principal beliefs are that

(a) methodological discipline is the key influence on the general efficiency of the process itself,

(b) the disciplined methodology reduces the cost and complexity of the process and enhances the predictability of the process as well,

(c) the preferred direction of both location and dispersion differences on process aspects is clear and undebatable, due to the tangibleness of the process aspects themselves and the direct applicability of expected values and variations in terms of average cost estimates and tightness of cost estimates,

(d) "mental cohesiveness" (or conceptual integrity [Brooks 75; pp. 41-50]) is the key influence on the general quality of the product itself,

(e) a programming team is naturally burdened (relative to an individual programmer) by the organizational overhead and risk of error-prone misunderstanding inherent in coordinating and interfacing the thoughts and efforts of those on the team,

(f) the disciplined methodology induces an effective mental cohesiveness, enabling a programming team to behave more like an individual programmer with respect to conceptual control over the program, its design, its structure, etc., because of the discipline's antiregressive, complexity-controlling [Belady and Lehman 76; p. 245] effect that compensates for the inherent organizational overhead of a team, and

(g) the preferred direction of both location and dispersion differences on product aspects is not always clear (occasionally subject to diverging viewpoints), due to the intangibleness of many of the product aspects and a general lack of understanding regarding the implication of dispersion comparisons themselves for product aspects.

Against the background of these general beliefs and basic suppositions, each possible comparison outcome takes on a new meaning, depending on whether it would substantiate or contravene the general beliefs. For process aspects,

(1) outcome $DT < AI = AT$, the supposition itself, is directly supportive of the beliefs;

(2) outcomes $DT < AI < AT$ and $DT < AT < AI$, which are completely differentiated variations of the supposition's main theme, are indirectly supportive of the beliefs, especially when $DT < AI = AT$ is the stronger of the two corresponding partially differentiated outcomes;

(3) outcome $AI = AT = DT$ may discredit the beliefs, or it may be considered neutral for anyone of several possible reasons [(a) the critical level for a non-null outcome is just not low enough, so the aspect defaults to the null outcome; (b) the aspect simply reflects something characteristic of the application itself (or another factor common to all the groups in the experiment); or (c) the aspect actually measures something fundamental to the software development phenomenon in general and would always result in the null outcome]; and

(4) all other outcomes discredit the beliefs.

For product aspects,

(1) outcomes $AT \neq DT = AI$ [$AT < DT = AI$, $DT = AI < AT$], the supposition itself, are directly supportive of the beliefs;

(2) outcomes $AI < DT < AT$ and $AT < DT < AI$, which may be considered as approximations of the suppositions (DT is distinct from AT but falls short of AI, due to lack of

experience or maturity in the disciplined methodology), are indirectly supportive of the beliefs, especially when DT = AI < AT and AT < DT = AI (respectively) are the stronger of the two corresponding partially differentiated outcomes;

(3) outcome AI = AT = DT may discredit the beliefs, or it may be considered neutral for anyone of several possible reasons [(a) the critical level for a non-null outcome is just not low enough, so the aspect defaults to the null outcome; (b) the aspect simply reflects something characteristic of the application itself (or another factor common to all the groups in the experiment); (c) the aspect actually measures something fundamental to the software development phenomenon in general and would always result in the null outcome; or (d) several of the study's hit-and-miss collection of "exploratory" product aspects are simply duds and may be ignored as useless software measures]; and

(4) all other outcomes discredit one or more of the beliefs.

Thus the interpretation of the study's findings according to the basic suppositions consists simply of a general assessment of how well the research conclusions have borne out the basic suppositions and how well the experimental evidence substantiates the general beliefs. On the whole, the study's findings positively support the general beliefs presented above, although a few conclusions exist which are directly inconsistent with the suppositions or difficult to allay individually.

Support for the beliefs was relatively stronger on process aspects than on product aspects, and in location comparisons than in dispersion comparisons. Overwhelming support came in the category of location comparisons on process aspects in which the research conclusions are distinguished by extremely low critical levels and by near unanimity with the basic supposition. In the category of dispersion comparisons on process aspects, only two outcomes indicated any distinction among the groups: one aspect supported the study's beliefs and one aspect showed an explainable exception to them. Fairly strong support also came in the category of location comparisons on product aspects for which the only negative evidence (besides the neutral AI = AT = DT conclusions) appeared in the form of several AI ≠ AT = DT conclusions. They indicate some areas in which the disciplined methodology was apparently ineffective in modifying a team's behavior toward that of an individual, probably due to a lack of fully developed training/experience with the methodology. Comparatively weaker support for the study's beliefs was recorded in the category of dispersion comparisons on product aspects. Although the suppositions were borne out in a number of the conclusions, there were also several distinctions of various forms which contravene the suppositions.

Thus, according to this interpretation, the study's findings strongly substantiate the claims that

(a) methodological discipline is the key influence on the general efficiency of the software development process, and that

(b) the disciplined methodology significantly reduces the material costs of software development.

The claims that

(a) mental cohesiveness is the key influence on the general quality of the software development product, that

(b) an ad hoc team is mentally burdened by organizational overhead compared to an individual, and that

(c) the disciplined methodology offsets the mental burden of organizational overhead and enables a team to behave more like an individual relative to the product itself,

are moderately substantiated by the study's findings, with particularly mixed evidence for dispersion comparisons on product aspects.

<u>It should be noted</u> that there is a simpler, better-supported interpretive model for the location results alone. With the beliefs that a disciplined methodology provides for the minimum

process cost and results in a product which in some aspects approximates the product of an individual and at worst approximates the product developed by an ad hoc team, the suppositions are $DT \leq AI, AT$ with respect to process and $AI \leq DT \leq AT$ or $AT \leq DT \leq AI$ with respect to product. The study's findings support these suppositions without exception.

<u>According to Programming Aspect Classification</u>:

Before presenting the interpretations according to a classification of the programming aspects, an explanation is in order regarding this classification and its motivation. It is desirable to make general interpretations in view of the way certain general programming issues are reflected among the individual programming aspects. For this purpose, the aspects considered in this study were grouped into (so-called) programming aspect classes. Each class consists of aspects which are related by some common feature (for example, all aspects relating to the program's statements, statement types, statement nesting, etc.), and the classes are not necessarily disjoint (i.e., a given aspect may be included in two or more classes). A unique higher-level programming issue (in the example, control structure organization) is associated with each class.

The programming aspects of this study were organized into a hierarchy of nine aspect classes (with about 10% overlap overall), outlined as follows:

<u>Higher-Level Programming Issue</u>:	<u>Class</u>:
Development Process Efficiency	
Effort (Job Steps)	I
Errors (Program Changes)	II
Final Product Quality	
Gross Size	III
Control-Construct Structure	IV
Data Variable Organization	V
Modularity	
Packaging Structure	VI
Invocation Organization	VII
Inter-Segment Communication	
Via Parameters	VIII
Via Global Variables	IX

The individual aspects comprising each class, together with the corresponding conclusions, are listed by classes in Tables 5.1

Table 5.1 Conclusions for Class I, Effort (Job Steps)

programming aspect	location comparison outcome	location critical level	dispersion comparison outcome	dispersion critical level
COMPUTER JOB STEPS	DT < AI = AT	0.0036	= =	
MODULE COMPILATIONS	DT < AI = AT	0.0223	= =	
UNIQUE	DT < AI = AT	0.0110	= =	
IDENTICAL	= =		= =	
PROGRAM EXECUTIONS	DT < AI = AT	0.0221	= =	
MISCELLANEOUS	DT < AI = AT	0.1445	AT = DT < AI	0.0775
ESSENTIAL JOB STEPS	DT < AI = AT	0.0037	= =	
AVERAGE UNIQUE COMPILATIONS PER MODULE	DT < AI = AT	0.0883	= =	
MAX UNIQUE COMPILATIONS F.A.O. MODULE	DT < AI = AT	0.1180	DT < AI < AT	& .0514

alternative conclusions (from Table 4) showing relaxed differentiation:
(correspondence indicated via the & symbol)

			DT < AI = AT	& .0036
			DT = AI < AT	& .0511

Table 5.2 Conclusions for Class II, Errors (Program Changes)

programming aspect	location comparison outcome	location critical level	dispersion comparison outcome	dispersion critical level
PROGRAM CHANGES	DT < AI < AT	& .1848	= =	

alternative conclusions (from Table 4) showing relaxed differentiation:
(correspondence indicated via the & symbol)

	DT < AI = AT	& .0037		
	DT = AI < AT	& .1846		

Table 5.3 Conclusions for Class III, Gross Size

programming aspect	location comparison outcome	location critical level	dispersion comparison outcome	dispersion critical level
MODULES	= =		= =	
AVERAGE SEGMENTS PER MODULE	= =		DT = AI < AT	0.0218
AVERAGE GLOBAL VARIABLES PER MODULE	= =		= =	
SEGMENTS	AI < AT = DT	0.0634	= =	
AVERAGE STATEMENTS PER SEGMENT	AT = DT < AI	0.1706	= =	
AVERAGE NONGLOBAL VARIABLES PER SEGMENT	= =		= =	
PARAMETER	AI < AT = DT	0.1748	= =	
LOCAL	= =		= =	
DATA VARIABLES	AI < AT = DT	0.0698	= =	
DATA VARIABLE SCOPE COUNTS \ GLOBAL	AI < AT = DT	0.1476	AI = AT < DT	0.1241
DATA VARIABLE SCOPE COUNTS \ NONGLOBAL	= =		= =	
PARAMETER	AI < AT = DT	0.1271	AI = AT < DT	0.1061
LOCAL	= =		= =	
LINES	AI < DT < AT	& .1194	= =	
STATEMENTS	= =		AT < DT = AI	0.1954
AVERAGE TOKENS PER STATEMENT	= =		AI = AT < DT	0.1061
TOKENS	= =		= =	

alternative conclusions (from Table 4) showing relaxed differentiation:
(correspondence indicated via the & symbol)

	DT = AI < AT	& .0617		
	AI < AT = DT	& .1132		

Table 5.4 Conclusions for Class IV, Control-Construct Structure

programming aspect	location comparison outcome	location critical level	dispersion comparison outcome	dispersion critical level
STATEMENTS	= =		AT < DT = AI	0.1954
STATEMENT TYPE COUNTS :				
:=	= =		= =	
IF	DT = AI < AT	0.0780	= =	
CASE	= =		= =	
WHILE	= =		= =	
EXIT	= =		= =	
(PROC)CALL	= =		DT < AI = AT	0.0325
NONINTRINSIC	= =		DT < AI = AT	0.1862
INTRINSIC	DT = AI < AT	0.1732	= =	
RETURN	DT = AI < AT	0.0860	DT < AI < AT	& .1398
STATEMENT TYPE PERCENTAGES :				
:=	= =		= =	
IF	DT = AI < AT	0.1069	= =	
CASE	= =		= =	
WHILE	= =		= =	
EXIT	= =		= =	
(PROC)CALL	= =		= =	
NONINTRINSIC	= =		= =	
INTRINSIC	= =		= =	
RETURN	= =		DT = AI < AT	0.0401
AVERAGE STATEMENT NESTING LEVEL	= =		= =	
DECISIONS	DT = AI < AT	0.1468	= =	
FUNCTION CALLS	= =		= =	
NONINTRINSIC	= =		= =	
INTRINSIC	= =		= =	

alternative conclusions (from Table 4) showing relaxed differenciation:
(correspondence indicated via the & symbol)

			DT = AI < AT	& .0035
			DT < AI = AT	& .1395

Table 5.5 Conclusions for Class V, Data Variable Organization

programming aspect	location comparison outcome	location critical level	dispersion comparison outcome	dispersion critical level
DATA VARIABLES	AI < AT = DT	0.0698	= =	
DATA VARIABLE SCOPE COUNTS :				
GLOBAL	AI < AT = DT	0.1476	AI = AT < DT	0.1241
ENTRY	= =		= =	
MODIFIED	= =		= =	
UNMODIFIED	= =		= =	
NONENTRY	= =		= =	
MODIFIED	= =		= =	
UNMODIFIED	= =		= =	
MODIFIED	AI < AT = DT	0.1614	= =	
UNMODIFIED	= =		= =	
NONGLOBAL	= =		= =	
PARAMETER	AI < AT = DT	0.1271	AI = AT < DT	0.1061
VALUE	= =		= =	
REFERENCE	= =		AI < AT = DT	0.0199
LOCAL	= =		= =	
DATA VARIABLE SCOPE PERCENTAGES :				
GLOBAL	= =		AI = AT < DT	0.0750
ENTRY	= =		= =	
MODIFIED	= =		= =	
UNMODIFIED	= =		= =	
NONENTRY	= =		= =	
MODIFIED	= =		DT < AI = AT	0.0218
UNMODIFIED	= =		= =	
MODIFIED	= =		= =	
UNMODIFIED	= =		= =	
NONGLOBAL	= =		AI = AT < DT	0.0750
PARAMETER	AI < AT = DT	0.1507	AI = AT < DT	0.0557
VALUE	= =		AI = AT < DT	0.0943
REFERENCE	= =		AI < AT = DT	0.1529
LOCAL	AT = DT < AI	0.1090	= =	
AVERAGE GLOBAL VARIABLES PER MODULE	= =		= =	
ENTRY	= =		= =	
NONENTRY	= =		= =	
MODIFIED	= =		DT = AI < AT	0.1100
UNMODIFIED	= =		= =	
AVERAGE NONGLOBAL VARIABLES PER SEGMENT	= =		= =	
PARAMETER	AI < AT = DT	0.1748	= =	
LOCAL	= =		= =	

Table 5.6 Conclusions for Class VI, Packaging Structure

programming aspect	location comparison outcome	location critical level	dispersion comparison outcome	dispersion critical level
MODULES	= =		= =	
AVERAGE SEGMENTS PER MODULE	= =		DT = AI < AT	0.0218
AVERAGE GLOBAL VARIABLES PER MODULE	= =		= =	
SEGMENTS	AI < AT = DT	0.0634	= =	
SEGMENT TYPE COUNTS \ FUNCTION	= =		= =	
SEGMENT TYPE COUNTS \ PROCEDURE	= =		= =	
SEGMENT TYPE PERCENTAGES \ FUNCTION	= =		= =	
SEGMENT TYPE PERCENTAGES \ PROCEDURE	= =		= =	
AVERAGE STATEMENTS PER SEGMENT	AT = DT < AI	0.1706	= =	
AVERAGE NONGLOBAL VARIABLES PER SEGMENT	= =		= =	
PARAMETER	AI < AT = DT	0.1748	= =	
LOCAL	= =		= =	

Table 5.7 Conclusions for Class VII, Invocation Organization

programming aspect	location comparison outcome	location critical level	dispersion comparison outcome	dispersion critical level
INVOCATIONS	= =		AT = DT < AI	0.0206
FUNCTION	= =		= =	
NONINTRINSIC	= =		= =	
INTRINSIC	= =		= =	
PROCEDURE	= =		DT < AI = AT	0.0325
NONINTRINSIC	= =		DT < AI = AT	0.1862
INTRINSIC	DT = AI < AT	0.1732	= =	
NONINTRINSIC	= =		AT = DT < AI	0.0510
INTRINSIC	DT = AI < AT	0.0435	= =	
AVG INVOCATIONS PER (CALLING) SEGMENT	= =		= =	
FUNCTION	= =		= =	
NONINTRINSIC	= =		= =	
INTRINSIC	= =		= =	
PROCEDURE	= =		= =	
NONINTRINSIC	= =		= =	
INTRINSIC	= =		DT < AI = AT	0.0653
NONINTRINSIC	AT = DT < AI	0.1699	= =	
INTRINSIC	= =		= =	
AVG INVOCATIONS PER (CALLED) SEGMENT	AT = DT < AI	0.1699	= =	
FUNCTION	AT = DT < AI	0.1936	AT < DT = AI	0.1411
PROCEDURE	= =		= =	

Table 5.8 Conclusions for Class VIII, Communication via Parameters

programming aspect	location comparison outcome	location critical level	dispersion comparison outcome	dispersion critical level
DATA VARIABLE SCOPE COUNTS\NONGLOBAL :				
PARAMETER	AI < AT = DT	0.1271	AI = AT < DT	0.1061
VALUE	= =		= =	
REFERENCE	= =		AI < AT = DT	0.0199
AVG NONGLOBAL VARIABLES PER SEGMENT :	= =		= =	
PARAMETER	AI < AT = DT	0.1748	= =	
PARAMETER PASSAGE TYPE PERCENTAGES :				
VALUE	= =		AI < AT = DT	0.1606
REFERENCE	= =		AI < AT = DT	0.1606

Table 5.9 Conclusions for Class IX, Communication via Global Variables

programming aspect	location comparison outcome	location critical level	dispersion comparison outcome	dispersion critical level
DATA VARIABLE SCOPE COUNTS \ GLOBAL	AI < AT = DT	0.1476	AI = AT < DT	0.1241
ENTRY	" "		" "	
MODIFIED	" "		" "	
UNMODIFIED	" "		" "	
NONENTRY	" "		" "	
MODIFIED	" "		" "	
UNMODIFIED	" "		" "	
MODIFIED	AI < AT = DT	0.1614	" "	
UNMODIFIED	" "		" "	
AVERAGE GLOBAL VARIABLES PER MODULE	" "		" "	
ENTRY	" "		" "	
NONENTRY	" "		" "	
MODIFIED	" "		DT = AI < AT	0.1100
UNMODIFIED	" "		" "	
(SEG,GLOBAL) ACTUAL USAGE PAIRS	" "		" "	
ENTRY	" "		" "	
MODIFIED	" "		" "	
UNMODIFIED	" "		" "	
NONENTRY	" "		" "	
MODIFIED	" "		" "	
UNMODIFIED	" "		" "	
MODIFIED	" "		AT < DT = AI	0.1061
UNMODIFIED	" "		" "	
(SEG,GLOBAL) POSSIBLE USAGE PAIRS	AI < AT = DT	0.1227	AI < DT < AT	& .0523
ENTRY	" "		" "	
MODIFIED	" "		" "	
UNMODIFIED	" "		" "	
NONENTRY	" "		AI < AT = DT	0.0786
MODIFIED	" "		DT = AI < AT	0.0510
UNMODIFIED	" "		AI < DT < AT	@ .1727
MODIFIED	" "		" "	
UNMODIFIED	" "		" "	
(SEG,GLOBAL) USAGE RELATIVE PERCENTAGES	" "		" "	
ENTRY	AT < DT < AI	# .1173	" "	
MODIFIED	AT < DT < AI	$ .1232	" "	
UNMODIFIED	" "		" "	
NONENTRY	" "		" "	
MODIFIED	" "		" "	
UNMODIFIED	AT < DT = AI	0.1546	" "	
MODIFIED	" "		" "	
UNMODIFIED	" "		" "	
(SEG,GLOBAL,SEG) DATA BINDINGS :				
ACTUAL	" "		" "	
SUBFUNCTIONAL	" "		" "	
INDEPENDENT	" "		AI < AT = DT	0.1963
POSSIBLE	DT = AI < AT	0.1861	DT = AI < AT	0.1529
RELATIVE PERCENTAGE	" "		" "	

alternative conclusions (from Table 4) showing relaxed differentiation:
(correspondence indicated via the &, @, #, and $ symbols)

	location comparison outcome	location critical level	dispersion comparison outcome	dispersion critical level
			AI < AT = DT	& .0207
			DT = AI < AT	& .0511
	AT < DT = AI	# .0826		
	AT = DT < AI	# .1111		
			AI < AT = DT	@ .1167
			DT = AI < AT	@ .1561
	AT < DT = AI	$ .1132		
	AT = DT < AI	$ .1132		

through 5.9. For each aspect class, it is interesting to jointly interpret the individual outcomes in an overall manner in order to see something of how these higher-level issues are affected by the factors of team size and methodological discipline.

Class I:

Within Class I (process aspects dealing with COMPUTER JOB STEPS), there is strong evidence of an important difference among the groups, in favor of the disciplined methodology, with respect to average development costs. As a class, these aspects directly reflect the frequency of computer system operations (i.e., module compilations and test program executions) during development. They are one possible way of measuring machine costs, in units of basic operations rather than monetary charges. Assuming each computer system operation involves a certain expenditure of the programmer's time and effort (e.g., effective terminal contact, test result evaluation), these aspects indirectly reflect human costs of development (at least that portion not devoted to design work).

The strength of the evidence supporting a difference with respect to location comparisons within this class is based on both (a) the near unanimity [8 out of 9 aspects] of the DT < AI = AT outcome and (b) the very low critical levels [<.025 for 5 aspects] involved. Indeed, the single exception among the location comparisons (AI = AT = DT on COMPUTER JOB STEPS\MODULE COMPILATIONS\IDENTICAL) is readily explained as a direct consequence of the fact that all teams made essentially similar usage (or nonuse, in this case, since identical compilations were not uncommon) of the on-line storage capability (for saving relocatable modules and thus avoiding identical recompilations). This was expected since all teams had been provided with identical storage capability, but without any training or urging to use it. The conclusions on location comparisons within this class are interpreted as demonstrating that

employment of the disciplined methodology by a

> programming team reduces the average costs, both machine and human, of software development, relative to both individual programmers and programming teams not employing the methodology.

Examination of the raw data scores themselves indicates the magnitude of this reduction to be on the order of 2 to 1 (i.e., 50%) or better.

With respect to dispersion comparisons within this class, the evidence generally failed to make any distinctions among the groups [AI = AT = DT on 7 out of 9 aspects]. These null conclusions in dispersion comparisons are interpreted as demonstrating that

> variability of software development costs, especially machine costs, is relatively insensitive to the factors of programming team size and degree of methodological discipline.

The two exceptions on individual process aspects both deserve mention. The COMPUTER JOB STEPS\MISCELLANEOUS aspect showed a AT = DT < AI dispersion distinction among the groups, reflecting the wider-spread behavior (as expected) of individual programmers relative to programming teams in the area of building on-line tools to indirectly support software development (e.g., stand-alone module drivers, one-shot auxiliary computations, table generators, unanticipated debugging stubs, etc.). The MAX UNIQUE COMPILATIONS F.A.O. MODULE aspect showed a DT < AI = AT dispersion distinction among the groups at an extremely low critical level [<.005], reflecting the lower variation (increased predictability) of the disciplined teams relative to the ad hoc teams and individuals in terms of "worst case" compilation costs for any one module. The additional AI < AT distinction for this comparison is clearly attributable to the fact that several teams in group AT built monolithic single-module systems, yielding rather inflated raw scores for this aspect.

Class II:

Within Class II (the process aspect PROGRAM CHANGES), there is strong evidence of an important difference among the groups, again in favor of the disciplined methodology, with respect to average number of errors encountered during implementation. Appendix 1 contains a detailed explanation of how program changes are counted. This aspect directly reflects the amount of textual revision to the source code during (postdesign) development. Claiming that textual revisions are generally necessitated by errors encountered while building, testing, and debugging software, recent research [Dunsmore and Gannon 77] has confirmed a high (rank order) correlation of total program changes (as counted automatically according to a specific algorithm) with total error occurrences (as tabulated manually from exhaustive scrutiny of source code and test results) during software implementation. This aspect is thus a reasonable measure of the relative number of programming errors encountered outside of design work. Assuming each textual revision involves a certain expenditure of the programmer's effort (e.g., planning the revision, on-line editing of source code), this aspect indirectly reflects the level of human effort devoted to implementation.

With respect to location comparison, the strength of the evidence supporting a difference among the groups is based on the very low critical level [<.005] for the DT < AI = AT outcome. The additional trend toward AI < AT is much less pronounced in the data. The interpretation is that

> the disciplined methodology effectively reduced the average number of errors encountered during software implementation.

This was expected since the methodology purposely emphasizes the criticality of the design phase and subjects the software design (code) to through reading and review prior to coding (key-in or testing), enhancing error detection and correction prior to implementation (testing).

With respect to dispersion comparison, no distinction among the groups was apparent, with the interpretation that

> variability in the number of errors encountered during implementation was essentially uniform across all three programming environments considered.

Class III:

Within Class III (product aspects dealing with the gross size of the software at various hierarchical levels), there is evidence of certain consistent differences among the groups with respect to both average size and variability of size. As a class, these aspects directly reflect the number of objects and the average number of component (sub)objects per object, according to the hierarchical organization (imposed by the programming language) of the software itself into objects such as modules, segments, data variables, lines, statements, and tokens.

With respect to location comparisons within this class, the non-null conclusions [7 out of 17 aspects] are nearly unanimous [5 out of 7] in the $AI < AT = DT$ outcome. The interpretation is that individuals tend to produce software which is smaller (in certain ways) on the average than that produced by teams. It is unclear whether such spareness of expression, primarily in segments, global variables, and formal parameters, is advantageous or not. The two non-null exceptions to this $AI < AT = DT$ trend deserve mention, since the one is only nominally exceptional and actually supportive of the tendency upon closer inspection, while the other indicates a size aspect in which the disciplined methodology enabled programming teams to break out of the pattern of distinction from individual programmers. The $AT = DT < AI$ outcome on AVERAGE STATEMENTS PER SEGMENT is a simple consequence of the outcome for the number of STATEMENTS ($AI = AT = DT$) and the outcome for the number of SEGMENTS ($AI < AT = DT$) and it still fits the overall pattern of $AI \neq AT = DT$ on location differences on size aspects. On the LINES aspect, the $DT = AI < AT$ distinction breaks the pattern since DT is associated with AI and not with AT. Since the number of statements was roughly the same for all three groups, this difference must be due mainly to the stylistic manner of arranging the source code (which was free-format with respect to line boundaries), to the amount of documentation comments within the source code, and to the number of lines taken up in data variable declarations.

With respect to dispersion comparisons within this class, the few aspects which do indicate any distinction among the groups [5 out of 17 aspects] seem to concur on the AI = AT < DT outcome. This pattern, which associates increased variation in certain size aspects with the disciplined methodology, is somewhat surprising and lacks an intuitive explanation in terms of the experimental factors. The exception DT = AI < AT on AVERAGE SEGMENTS PER MODULE is really an exaggeration due to the fact of several AT teams implementing monolithic single-module systems, as mentioned above. The exception AT < DT = AI on STATEMENTS is only a very slight trend, reflecting the fact that the AT products rather consistently contained the largest numbers of statements.

One overall observation for Class III is that while certain distinctions did consistently appear (especially for location but also for dispersion comparisons) at the middle levels of the hierarchical scale [segments, data variables, lines, and statements], no distinctions appeared at either the highest [modules] or lowest [tokens] levels of size. The null conclusions for size in modules and average module size seem attributable to the fact that particular programming tasks or application domains often have certain standard approaches at the topmost conceptual levels which strongly influence the organization of software systems at this highest level of gross size. In this case, the two-pass symbol-table/scanning/parsing/code-generation approach is extremely common for language translation problems (i.e., compilers), regardless of the particular parsing technique or symbol table organization employed, and the modules of nearly every system in the study directly reflected this common approach. The null conclusions for size in tokens is interpretable in view of Halstead's software science concepts [Halstead 77], according to which the program length N is predictable from the number η_2^* of basic input-output parameters and the language level λ. Since the functional specification, the application area, and the implementation language were all fixed in the study, both η_2^* and λ are essentially constant for each of the software systems, implying essentially constant lengths N as measured in terms of operators and operands. Considering the number of tokens as roughly equivalent to program length N, the study's data seem to support the software science concepts in this instance.

Class IV:

Within Class IV (product aspects dealing with the software's organization according to statements, constructs, and control structures), there are only a few distinctions made between the groups.

With respect to location comparisons, the few [5 out of 24] aspects that showed any distinction at all were unanimous in concluding DT = AI < AT. Essentially, three particular issues were involved. The STATEMENTS TYPE COUNTS\IF, STATEMENT TYPE PERCENTAGES\IF, and DECISIONS aspects are all related to the frequency of programmer-coded decisions in the software product. Their common outcome DT = AI < AT is interpreted as demonstrating an important area in which the disciplined methodology causes a programming team to behave like an individual programmer. The number of decisions has been commonly accepted, and even formalized [McCabe 76], as a measure of program complexity since more decisions create more paths through the code. Thus, the disciplined methodology effectively reduced the average complexity from what it otherwise would have been. The STATEMENT TYPE COUNTS\RETURN aspect indicates a difference between the ad hoc teams and the other two groups. Since the EXIT and RETURN statements are restricted forms of GOTOs, this difference seems to hint at another area in which the disciplined methodology improves conceptual control over program structure. The STATEMENT TYPE

COUNTS\(PROC)CALL\INTRINSIC aspect also indicates a slight trend in the area of the frequency of input-output operations, which seems interpretable only as a result of stylistic differences.

With respect to dispersion comparisons, only two particular issues were involved. The STATEMENT TYPE COUNTS\RETURN and STATEMENT TYPE PERCENTAGE\RETURN aspects both indicated a strong DT = AI < AT difference, suggesting that the frequency of these restricted GOTOs is an area in which the disciplined methodology reduces variability, causing a programming team to behave more like an individual programmer. The STATEMENT TYPE COUNTS\(PROC)CALL and STATEMENT TYPE COUNTS\(PROC)CALL\NONINTRINSIC aspects both showed a DT < AI = AT distinction among the groups, which is dealt with more appropriately within Class VII below.

In summary of Class IV, the interpretation is that the functional component of control-construct organization is largely unaffected by the team size and methodological discipline factors, probably due to the overriding effect of project/task uniformity/commonality. However, two facets of the control component that were influenced were the frequency of decisions (especially IF statements) and the frequency of restricted GOTOs (especially RETURN statements). For these aspects, the disicplined methodology altered the control structure (and reduced the complexity) of a team's product to that of an individual's product.

Class V:

Within Class V (product aspects dealing with data variables and their organization within the software), there are several distinctions among the groups, with an overall trend for both the location and dispersion comparisons. Data variable organization was, however, not emphasized in the disciplined methodology, nor in the academic course which the participants in group DT were taking. With respect to location comparisons, all aspects showing any distinction at all were unanimous in concluding AI ≠ AT = DT.

The trend for individuals to differ from teams, regardless of the disciplined methodology, appears not only for the total number of data variables declared, but also for data variables at each scope level (global, parameter, local) in one fashion or another. The difference regarding formal parameters is especially prominent, since it shows up for their raw count frequency, their normalized percentage frequency, and their average frequency per natural enclosure (segment). With respect to dispersion comparisons, the apparent overall trend for aspects which show a distinction is toward the AI = AT < DT outcome. No particular interpretation in view of the experimental factors seems appropriate. Exceptions to this trend appeared for both the raw count and percentage of call-by-reference paramenters (both AI < AT = DT), as well as two other aspects.

Class VI:

Within Class VI (product aspects dealing with modularity in terms of the packaging structure), there are essentially no distinctions among the groups, except for two location comparison issues. Most of the aspects in this class are also members of Class III, Gross Size, but are (re)considered here to focus attention upon the packaging characteristics of modularity (i.e., how the source code is divided into modules and segments, what type of segments, etc.). The disciplined methodology did not explicitly include (nor did group DT's course work cover) concepts of modularization or criteria for evaluating good modularity; hence, no particular distinctions among the groups were expected in this area (Classes VI and VII).

With respect to location comparisons, the AI < AT = DT outcome for the SEGMENTS aspects, along with the companion outcome AT = DT < AI for the AVERAGE STATEMENTS PER SEGMENT aspect (as explained under Class III above), indicates one area of packaging that is apparently sensitive to the team size factor. Individual programmers built the system with fewer, but larger (on the average), segments than either the ad hoc teams or the disciplined teams. The AI < AT = DT outcome for the AVERAGE NONGLOBAL VARIABLES PER SEGMENT\PARAMETER aspect indicates that average "calling sequence" length, curiously enough, is another area of packaging sensitive to team size. With respect to dispersion comparisons, there really were no differences, since the single non-null outcome for AVERAGE SEGMENTS PER MODULE is actually a fluke (raw scores for AT are exaggerated by the several monolithic systems) as explained above. The overall interpretation for this class is that

> modularity, in the sense of packaging code into segments and modules, is essentially unaffected by team size or methodological discipline, except for a tendency by individual programmers toward fewer, longer segments than programming teams.

Class VII:

Within Class VII (product aspects dealing with modularity in terms of the invocation structure), there are two distinction trends for location comparisons, but no clear pattern for the dispersion comparison conclusions. This class consists of raw counts and average-per-segment frequencies for invocations (procedure CALL statements or function references in expressions) and is considered separately from the previous class since modularity involves not only the manner in which the system is packaged, but also the frequency with which the pieces are invoked. For the raw count frequencies of calls to intrinsic procedures and intrinsic routines, the trend is for the individuals and disciplined teams to exhibit fewer calls than the ad hoc teams. These intrinsic procedures are almost exclusively the input-output operations of the language, while the intrinsic functions are mainly data type conversion routines. The second trend for location comparisons occurs for two aspects (a third aspect is actually redundant) related to the average frequency of calls to programmer-defined routines, in which the individuals display higher average frequency than either type of team. This seems coupled with group AI's preference for fewer but larger routines, as noted above. With respect to dispersion comparisons, several distinctions appear within this class, but no overall interpretation is readily apparent (except for a consistent reflection of a DT < AI difference, with AT falling in between, leaning one side or the other).

Class VIII:

Within Class VIII (product aspects dealing with inter-segment communication via formal parameters), there are only a few distinctions among the groups. With respect to location comparisons, the total frequency of parameters and the average frequency of parameters per segment both show a difference. The interpretation is that

> the individual programmers tend to incorporate less inter-segment communication via parameters, on the average, than either the ad hoc or the disciplined programming teams.

With respect to dispersion comparisons, in addition to the difference in the raw count of parameters referred to in Class V, there is a strong difference in the variability of the number of call-by-reference parameters, also apparent in the percentages-by-type-of parameter aspects. The interpretation is that

> the individual programmers were more consistent as a group in their use (in this case, avoidance) of reference parameters than either type of programming team.

Class IX:

Within Class IX (product aspects dealing with inter-segment communication via global variables), there are several differences among the groups, including two which indicate the beneficial influence of the disciplined methodology. This class is composed of aspects dealing with (a) frequency of globals, (b) average frequency of globals per module, (c) segment-global usage pairs (frequency of access paths from segments to globals), and (d) segment-global-segment data bindings [Stevens, Myers, and Constantine 74; pp. 118-119] (frequency of logical bindings between two different segments via a global variable which is modified by the first segment and referenced by the second).

With respect to location comparisons, there is the AI < AT = DT distinction in sheer numbers of globals, particularly globals which are modified during execution, as noted in Class V. However, when averaged per module, there appears to be no distinction in the frequency of globals. The AI < AT = DT difference in the number of possible segment-global access paths makes sense as the result of group AI having both fewer segments and fewer globals. All three groups had essentially similar average levels of actual segment-global access paths, but several differences appear in the relative percentage (actual-to-possible ratio) category. These three instances of AT < DT = AI differences indicate that the degree of "globality" for global variables was higher for the individuals and the disciplined teams than for the ad hoc teams. Finally, another AT ≠ DT = AI difference appears for the frequency of possible segment-global-segment data bindings, indicating a positive effect of the disciplined methodology in reducing the possible data coupling among segments. It may be noted that these last two categories of aspects, segment-global usage relative percentages and segment-global-segment data bindings, also reflect upon the quality of modularization, since good modularity should promote the degree of "globality" for globals and minimize the data coupling among segments. The interpretation here is that

> certain aspects of inter-segment communication via globals seems to be positively influenced, on the average, by the disciplined methodology.

With respect to dispersion comparisons, there is a diversity of differences in this class, without any unifying interpretation in terms of the experimental factors.

VI. Concluding Remarks

A practical methodology was designed and developed for experimentally and quantitatively investigating the software development phenomenon. It was employed to compare three particular software development environments and to evaluate the relative impact of a particular disciplined methodology (made up of so-called modern programming practices). The experiments were successful in measuring differences among programming environments and the results support the claim that disciplined methodology effectively improves both the process and product of software development.

One way to substantiate the claim for improved process is to measure the effectiveness of the particular programming methodology via the number of bugs initially in the system (i.e., in the initial source code) and the amount of effort required to remove them. (This criteria was independently suggested by Professor M. Shooman of Polytechnic Institute of New York while speaking recently on the subject of sofware reliability models.) Although neither of these measures was directly computed, they are each closely associated with one of the process aspects considered in the study: PROGRAM CHANGES and ESSENTIAL JOB STEPS, respectively. The statistical conclusions (on location comparison) for both these aspects affirmed DT < AI = AT outcomes at very low (<.01) significance levels, indicating that on the average the disciplined teams measured lower than either the ad hoc individuals or the ad hoc teams which both measured about the same. Thus, the evidence collected in this study strongly confirms the effectiveness of the disciplined methodology in building reliable software efficiently.

The second claim, that the product of a disciplined team should closely resemble that of a single individual since the disciplined methodology assures a semblence of conceptual integrity within a programming team, was partially substantiated.

In many product aspects the products developed using the disciplined methodology were either similar to or tended toward the products developed by the individuals. In no case did any of the measures show the disciplined teams' products to be worse than those developed by the ad hoc teams. It is felt that the superficiality of most of the product measures was chiefly responsible for the lack of stronger support for this second claim. The need for product measures with increased sensitivity to critical characteristics of software is very clear.

The results of these experiments will be used to guide further experiments and will act as a basis for analysis of software development products and processes in the Software Engineering Laboratory at NASA/GSFC [Basili et al. 77]. The intention is to persue this type of research, especially extending the study to include more sophisticated and promising programming aspects, such as Halstead's software science quantities [Halstead 77] and other software complexity metrics [McCabe 76].

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Appendix 1. Explanatory Notes for the Programming Aspects

The following numbered paragraphs, keyed to the list of aspects in Table 1, explain in detail the programming aspects considered in the study. Various system- or language-dependent terms (e.g., module, segment, intrinsic, entry) are also defined here.

(1) A computer job step is a single activity performed on a computer at the operating system command level which is inherent to the development effort and involves a nontrivial expenditure of computer or human resources. Typical job steps might include text editing, module compilation, program collection or link-editing, and program execution; however, operations such as querying the operating system for status information or requesting access to on-line files would not be considered as job steps. In this study, only module compilations and program executions are counted as COMPUTER JOB STEPS.

(2) A module compilation is an invocation of the implementation language processor on the source code of an individual module. In this study, only compilations of modules comprising the final software product (or logical predecessors thereof) are counted as COMPUTER JOB STEPS\MODULE COMPILATIONS.

(3) All MODULE COMPILATIONS are classified as either IDENTICAL or UNIQUE depending on whether or not the source code compiled is textually identical to that of a previous compilation. During the development process, each unique compilation was necessary in some sense, while an identical compilation could have been logically avoided by saving the relocatable output of a previous compilation for later reuse (except in the situation of undoing source code revisions after they have been tested and found to be erroneous or superfluous).

(4) A program execution is an invocation of a complete

programmer-developed program (after the necessary compilation(s) and collection or link-editing) upon some test data.

(5) A <u>miscellaneous job step</u> is an auxiliary compilation or execution of something other than the final software product. Only job steps counted as COMPUTER JOB STEPS, but not counted as COMPUTER JOB STEPS\MODULE COMPILATIONS or COMPUTER JOB STEPS\PROGRAM EXECUTIONS, are counted as COMPUTER JOB STEPS\MISCELLANEOUS.

(6) An <u>essential job step</u> is a computer job step which involves the final software product (or logical predecessors thereof) and could not have been avoided (by off-line computation or by on-line storage of previous compilations or results). In this study, the number of ESSENTIAL JOB STEPS is the sum of the number of COMPUTER JOB STEPS\MODULE COMPILATIONS\UNIQUE plus the number of COMPUTER JOB STEPS\PROGRAM EXECUTIONS.

(7) The number of AVERAGE UNIQUE COMPILATIONS PER MODULE is simply the number of COMPUTER JOB STEPS\MODULE COMPILATIONS\UNIQUE divided by the number of MODULES.

(8) The number of MAX UNIQUE COMPILATIONS F.A.O. MODULE is simply the maximum number of unique compilations for any one module of the final software product. F.A.O. stands for "for any one". Each unique compilation is associated (either directly or as a logical predecessor) with a particular module of the final product; their sum is computed for each module; and the maximum of the sums is taken.

(9) The <u>program changes</u> metric [Dunsmore and Gannon 77] is defined in terms of textual revisions in the source code of a module during the development period, from the time that module is first presented to the computer system, to the completion of the project. The rules for counting program changes --which are reproduced below from the paper referenced above with the kind permission of the authors-- are such that one program change

should represent approximately one conceptual change to the program.

The following each represent a single program change:
(a) one or more changes to a single statement,
(A single statement in a program represents a single concept and even multiple character changes to that statement represent mental activity with a single concept.)
(b) one or more statements inserted between existing statements,
(The contiguous group of statements inserted probably corresponds to a single abstract instruction.)
(c) a change to a single statement followed by the insertion of new statements.
(This instance probably represents a discovery that an existing statement is insufficient and that it must be altered and supplemented in order to achieve the single concept for which it was produced.)

However, the following are not counted as program changes:
(a) the deletion of one or more existing statements,
(Statements which are deleted must usually be replaced with other statements elsewhere. The inserted statements are counted; counting deletions as well would give double weight to such a change. Occasionally statements are deleted but not replaced; these are probably being used for debugging purposes and their deletion takes no great mental activity.)
(b) the insertion of standard output statements or special compiler-provided debugging directives,
(These are occasionally inserted in a wholesale fasion during debugging. When the problem is discerned, these are then all removed, and the actual ststement change takes place.)
(c) the insertion of blank lines, insertion of comments, revision of comments, and reformatting without alteration of existing statements.
(These are all judged to be cosmetic in nature.)

Program changes are counted automatically according to a specific algorithm which symbolically compares the source code from each pair of consecutive compilations of a particular module (or logical predecessor thereof). Thus the total number of program changes is a measure of the amount of textual revision to source code during (postdesign) system development.

(10) A <u>module</u> is a separately compiled portion of the complete software system. In the implementation language SIMPL-T, a typical module is a collection of the declarations of several global variables and the definitions of several segments. [In this study, only those modules which comprise the final product are counted as MODULES.]

(11) A <u>segment</u> is a collection of source code statements, together with declarations for the formal parameters and local variables manipulated by those statements, which may be invoked as

an operational unit. In the implementation language SIMPL-T, a segment is either a value-returning _function_ (invoked via reference in an expression) or else a non-value-returning _procedure_ (invoked via the CALL statement), and recursive segments are allowed and fully supported. The segment, function, and procedure of SIMPL-T correspond to the (sub)program, function, and subroutine of FORTRAN, respectively.

(12) The group of aspects named SEGMENT TYPE COUNTS, etc., gives the absolute number of programmer-defined segments of each type. The group of aspects named SEGMENT TYPE PERCENTAGES, etc., gives the relative percentage of each type of segment, compared with the total number of programmer-defined segments. The second group of aspects is computed from the first by simply dividing by the number of SEGMENTS, as a way of normalizing the segment type counts.

(13) Since segment definitions in the implementation language SIMPL-T occur within the context of a module, this provids a natural way to normalize (or average) the raw counts of segments. The AVERAGE SEGMENTS PER MODULE aspect represents the number of segments in a typical module. It is computed in the obvious way.

(14) The number of LINES is the total count of every textual line in the source code of the complete final product, including comments, compiler directives, variable declarations, executable statements, etc.

(15) The number of STATEMENTS counts only the executable constructs in the source code of the complete final product. These are high-level, structured-programming statements, including simple statements --such as assignment and procedure call-- as well as compound statements --such as if-then-else and while-do-- which have other statements nested within them. The implementation language SIMPL-T allows exactly seven different statement types (referred to by their distinguishing keyword or symbol) covering assignment (:=), alternation-selection (IF,

CASE), iteration (WHILE, EXIT), and procedure invocation (CALL, RETURN). Input-output operations are accomplished via calls to certain intrinsic procedures.

(16) The group of aspects named STATEMENT TYPE COUNTS, etc., gives the absolute number of executable statements of each type. The group of aspects named STATEMENT TYPE PERCENTAGES, etc., gives the relative percentage of each type of statement, compared with the total number of executable statements. The second group of aspects is computed from the first by simply dividing by the number of STATEMENTS, as a way of normalizing the statement type counts.

(17) As mentioned above, the := symbol denotes the assignment statement. It assigns the value of the expression on the right hand side to the variable on the left hand side.

(18) Both if-then and if-then-else constructs are counted as IF statements. Each IF statement allows the execution of either the then- or else-part statements, depending upon its Boolean expression.

(19) The CASE statement provides for selection from several alternatives, depending upon the value of an expression. In the implementation language SIMPL-T, exactly one of the alternatives (or an optional else-part) is selected per execution of a CASE, a list of constants is explicitly given for each alternative, and selection is based upon the equality of the expression value with one of the constants. A case construct with n alternatives is logically and semantically equivalent to a certain pattern of n nested if-then-else constructs.

(20) The WHILE statement is the only iteration or looping construct provided by the implementation language SIMPL-T. It allows the statements in the loop body to be executed repeatedly (zero or more times) depending upon a Boolean expression which is reevaluated at every iteration; the loop may also be terminated

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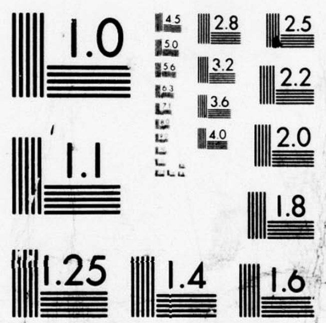

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via an EXIT statement. Each WHILE statement may be optionally labeled with a designator (referenced by EXIT statements) which uniquely identifies it from other nested WHILE statements.

(21) The EXIT statement allows the abnormal termination of iteration loops by unconditional transfer of control to the statement immediately following the WHILE statement. Thus it is a very restricted form of GOTO. This exiting may take place from any depth of nested loops, since the EXIT statement may optionally name a designator which identifies the loop to be exited; without such a designator only the immediately enclosing loop is exited.

(22) Since there are two types of segments in the implementation language SIMPL-T, there are two types of "calls" or segment invocations. Procedures are invoked via the CALL statement, and functions are invoked via reference in an expression. The counts for these separate constructs are reported separately as the (PROC)CALL and FUNCTION CALL aspects, and jointly as the INVOCATIONS aspect.

(23) <u>Intrinsic</u> means provided and defined by the implementation language; <u>nonintrinsic</u> means provided and defined by the programmer. These terms are used to distinguish built-in procedures or functions (which are supported by the compiler and utilized as primitives) from segments (which are written by the programmer himself). Nearly all of the intrinsic procedures provided by the implementation language SIMPL-T perform input-output operations and external data file manipulations. All of the intrinsic functions provided by SIMPL-T perform data type conversions and character string manipulations.

(24) The RETURN statement allows the abnormal termination of the current segment by unconditional resumption of the previously executing segment. Thus it is another very restricted form of GOTO. Within a function, a RETURN statement must specify an expression, the value of which becomes the value returned for the function invocation. Within a procedure, a RETURN statement must

not specify such an expression. Additionally, a simple RETURN statement is optional at the textual end of procedures; it will be implicitly assumed if not explicitly coded. In this study, the total number of explicitly coded and implicitly assumed RETURN statements, both from functions and procedures combined, is counted.

(25) The AVERAGE STATEMENTS PER SEGMENT aspect provides a way of normalizing the number of statements relative to their natural enclosure in a program, the segment. The measure also represents the length, in executable statements, of a typical segment of the program.

(26) In the implementation language SIMPL-T, both simple (e.g., assignment) and compound (e.g., if-then-else) statements may be nested inside other compound statements. A particular nesting level is associated with each statement, starting at 1 for a statement at the outermost level of each segment and increasing by 1 for successively nested statments. Nesting level can be displayed visually via proper and consistent indentation of the souce code listing.

(27) The number of DECISIONS is simply the sum of the numbers of IF, CASE, and WHILE statements within the complete source code. Each of these statements represents a unique (possibly repeated) run-time decision coded by the programmer. This count is closely associated with a recently proposed complexity metric [McCabe 76] which essentially reflects the number of binary-branching decisions represented in the source code.

(28) Tokens are the basic syntactic entities --such as keywords, operators, parentheses, identifiers, etc.-- that occur in a program statement. The average number of tokens per statement may be viewed as an indication of how much "information" a typical statement contains, how "powerful" a typical statement is, or how concisely the statements in general are coded.

(29) An invocation is simply the syntactic occurrence of a construct by which either a programmer-defined segment or a built-in routine is invoked from within another segment; both procedure calls and function references are counted as INVOCATIONS. They are (sub)classified by the type (i.e., function or procedure, nonintrinsic or intrinsic) of segment or routine being invoked.

(30) The group of aspects named AVG INVOCATIONS PER (CALLING) SEGMENT, etc., represents one way to normalize the absolute number of invocations. These aspects reflect the number of calls to programmer-defined segments and built-in routines from a typical programmer-defined segment. They are (sub)classified by the type of segment or routine being invoked. The measures for this group of aspects are computed by simply dividing each of the corresponding measures in the INVOCATIONS aspect group by the number of SEGMENTS.

(31) The group of aspects named AVG INVOCATIONS PER (CALLED) SEGMENT, etc., represents another way to normalize the absolute number of invocations. These aspects reflect the number of calls to a typical programmer-defined segment from other segments. They are (sub)classified by the type (i.e., function or procedure) of segment being invoked.

(32) A data variable is an individually named scalar or array of scalars. In the implementation language SIMPL-T, (a) there are three data types for scalars --integer, character, and (varying length) string--, (b) there is one kind of data structure (besides scalar) --single dimensional array, with zero-origin subscript range--, and (c) there are several levels of scope (as explained in note 33 below) for data variables. In addition, all data variables in a SIMPL-T program must be explicitly declared, with attributes fully specified. The number of DATA VARIABLES is computed by counting each of the data variables declared in the final software product once, regardless of type, structure, or scope. Note that each array is counted as a single data variable.

(33) In the implementation language SIMPL-T, data variables can have any one of essentially four levels of _scope_ --entry global, nonentry global, parameter, and local-- depending on where and how they are declared in the program. Note that the notion of scope deals only with static accessibility by name; the effective accessibility of any variable can always be extended by passing it as a parameter between segments. The scope levels are explained here (and presented in the aspect (sub)classifications) via a hierarchy of distinctions.

The primary distinction is between global and nonglobal. _Global_ variables are accessible by name to each of the segments in the module in which they are declared. _Nonglobal_ variables are accessible by name only to the single segment in which they are declared.

Global varaibles are secondarily distinguished into entry and nonentry. _Entry globals_ are actually accessible by name to each of the segments in several (two or more) modules: the module which declared it ENTRY, plus each of the modules which declared it EXTernal (as explained in note 34 below). _Nonentry globals_ are accessible by name only within the module in which they are declared.

Nonglobal variables are secondarily distinguished into formal parameter and local. Formal _parameters_ are accessible by name only within the enclosing (called) segment, but their values are not completely unrelated to the calling segment (as explained in note 36 below). _Locals_ are accessible by name only within the enclosing segment, and their values are completely isolated from any other segment.

(34) _Entry_ means that the data variable [or segment] is declared to be accessible from within other separately compiled modules (in which it must be explicitly declared as EXTernal). _Nonentry_ means that the data variable [or segment] is accessible only within the module in which it is declared [or defined]. In this study these terms are used pertaining only to global variables. "Entry global" actually constitutes an extra level of scope beyond "nonentry global". [Although the implementation

language SIMPL-T does allow the EXTernal attribute to be declared for local variables --just the enclosing segment has access to a global declared in a different module--, it is an extremely obscure and rarely used feature; it never occurred in any of the final software products examined in this study.]

(35) Modified means referred to, at least once in the program source code, in such a manner that the value of the data variable would be (re)set when (and if) the appropriate statements were to be executed. Data variables can be (re)set only by (a) being the "target" of an assignment statement, (b) being passed by reference to some programmer-defined segment or built-in routine, or (c) being named in an "input statement." This third case is really covered by the second case since all the "input statements" in SIMPL-T are actually calls to certain intrinsic procedures with passed-by-reference parameters. Unmodified means referred t throughout the program source code, in such a manner that the value of the data variable could never be (re)set during execution. These terms are used pertaining to global data variables; any global variable is allowed to have an initial value (constants only) specified in its declaration. Globals which are initialized but UNMODIFIED are particularly useful in SIMPL-T programs, serving as "named constants."

(36) The implementation language SIMPL-T allows two types of parameter passage. Pass-by-value means that the value of the actual argument is simply copied (upon invocation) into the corresponding formal parameter (which thereafter behaves like a local variable for all intents and purposes), with the effect that the called routine cannot modify the value of the calling segment's actual argument. Pass-by-reference means that the address of the actual argument --which must be a variable rather than an expression-- is passed (upon invocation) to the called routine, with the effect that any changes made by the called routine to the corresponding formal parameter will be reflected in the value of the calling segment's actual argument (upon return). In SIMPL-T, formal parameters which are scalars are normally

(default) passed by value, but they may be explicitly declared to be passed by reference; formal parameters which are arrays are always passed by reference.

(37) The group of aspects named DATA VARIABLE SCOPE COUNTS, etc., gives the absolute number of declared data variables according to each level of scope. The group of aspects named DATA VARIABLE SCOPE PERCENTAGES, etc., gives the relative percentage of variables at each scope level, compared with the total number of declared variables. The second group of aspects is computed from the first by simply dividing by the number of DATA VARIABLES, as a way of normalizing the data variable scope counts.

(38) Since data variable declarations in the implementation language SIMPL-T may only appear in certain contexts within the program --globals in the context of a module and and nonglobals in the context of a segment--, this provides a natural way to normalize (or average) the raw counts of data variables. The group of aspects named AVERAGE GLOBAL VARIABLES PER MODULE, etc., represent the number of globals declared for a typical module. They are computed by simply dividing each of the corresponding raw counts of global data variables by the number of MODULES. The group of aspects named AVERAGE NONGLOBAL VARIABLES PER SEGMENT, etc., represent the number of nonglobals declared for a typical segment. They are computed by simply dividing each of the corresponding raw counts of nonglobal data variables by the number of SEGMENTS.

(39) Since there are two types of parameter passing mechanisms in the implementation language SIMPL-T (as explained in note 36 above), it is desirable to normalize their raw frequencies into relative percentages, indicating the programmer's degree of "preference" for one type or the other. The group of aspects named PARAMETER PASSAGE TYPE PERCENTAGES, etc., gives the percentages of each type of parameter relative to the total number of parameters declared in the program. They are computed in the obvious way.

(40) A segment-global _usage pair_ (p,r) is simply an instance of a global variable r being used by a segment p (i.e., the global is either modified (set) or accessed (fetched) at least once within the statements of the segment). Each usage pair represents a unique "use connection" between a global and a segment. Usage pairs are (sub)classified by the type (i.e., entry or nonentry, modified or unmodified) of global data variable involved.

In this study, segment-global usage pairs were counted in three different ways. First, the (SEG,GLOBAL) ACTUAL USAGE PAIR counts are the absolute numbers of true usage pairs (p,r): the global variable r is actually used by segment p. They represent the true frequencies of use connections within the program. Second, the (SEG,GLOBAL) POSSIBLE USAGE PAIR counts are the absolute numbers of potential usage pairs (p,r), given the program's global variables and their declared scope: the scope of global variable r simply contains segment p, so that segment p could potentially modify or access r. These counts of possible usage pairs are computed as the sum of the number of segments in each global's scope. They represent a sort of "worst case" frequencies of use connections. Third, the (SEG,GLOBAL) USAGE RELATIVE PERCENTAGE counts are a way of normalizing the number of usage pairs since these measures are simply the ratios (expressed as percentages) of actual usage pairs to possible usage pairs. They represent the frequencies of true use connections relative to potential use connections. These usage pair relative percentage metrics are empirical estimates of the likelihood that an arbitrary segment uses (i.e., sets or fetches the value of) an arbitrary global variable.

(41) A segment-global-segment _data binding_ (p,r,q) is an occurrence of the following arrangement in a program [Stevens, Myers, and Constantine 74]: a segment p modifies (sets) a global variable r which is also accessed (fetched) by a segment q, with segment p different from segment q. The existence of a data binding (p,r,q) indicates that the behavior of segment q is probably dependent on the performance of segment p because of the data variable r, whose value is set by p and used by q. The

binding (p,r,q) is different from the binding (q,r,p) which may also exist; occurrences such as (p,r,p) are not counted as data bindings. Thus each (SEG,GLOBAL,SEG) DATA BINDING represents a unique communication path between a pair of segments via a global variable. The total number of (SEG,GLOBAL,SEG) DATA BINDINGS reflects the degree of a certain kind of "connectivity" (i.e., between segment pairs via globals) within a complete program.

(42) In this study, segment-global-segment data bindings were counted in three different ways. First, the ACTUAL count is the absolute number of true data bindings (p,r,q): the global variable r is actually modified by segment p and actually accessed by segment q. It represents the degree of true connectivity in the program. Second, the POSSIBLE count is the absolute number of potential data bindings (p,r,q), given the program's global variables and their declared scope: the scope of global variable r simply contains both segment p and segment q, so that segment p could potentially modify r and segment q could potentially access r. This count of POSSIBLE data bindings is computed as the sum of terms s*(s-1) for each global, where s is the number of segments in that global's scope; thus, it is fairly sensitive (numerically speaking) to the total number of SEGMENTS in a program. It represents a sort of "worst case" degree of potential connectivity. Third, the RELATIVE PERCENTAGE is a way of normalizing the number of data bindings since it is simply the quotient (expressed as a percentage) of the actual data bindings divided by the possible data bindings. It represents the degree of true connectivity relative to potential connectivity.

(43) Actual data bindings are (sub) classified as "subfunctional" or "independent" depending on the invocation relationship between the two segments. A data binding (p,r,q) is <u>subfunctional</u> if either of the two segments p or q can invoke the other, whether directly or indirectly (via a chain of intermediate invocations involving other segments). In this situation, the function of the one segment may be viewed as contributing to the overall function of the other segment. A data binding (p,r,q) is

independent if neither of the two segments p or q can invoke the other, whether directly or indirectly. The transitive closure of the call graph among the segments of a program is employed to make this distinction between subfunctional and independent.

(44) There exist several instances of duplicate programming aspects in the Table 1 listing. That is, certain logically unique aspects appear a second time with another name, in order to provide alternative views of the same metric and to achieve a certain degree of completeness within a set of related aspects. For example, the FUNCTION CALLS aspect and the STATEMENT TYPE COUNTS\(PROC)CALL aspect are listed (and categorized appropriately) from the viewpoint of the various type of constructs which comprise the the implementation language. But the very same metrics can be considered from the unifying viewpoint of the various subtype frequencies for segment invocations, and thus it is desirable to include the duplicate aspects INVOCATIONS\FUNCTIONS and INVOCATIONS\PROCEDURES as part of the natural categorization of INVOCATIONS. Listed below are the pairs of duplicate programming aspects that were considered in this study:

1. FUNCTION CALLS
   <=> INVOCATIONS\FUNCTION
2. FUNCTION CALLS\NONINTRINSIC
   <=> INVOCATIONS\FUNCTION\NONINTRINSIC
3. FUNCTION CALLS\INTRINSIC
   <=> INVOCATIONS\FUNCTION\INTRINSIC
4. STATEMENT TYPE COUNTS\(PROC)CALL
   <=> INVOCATIONS\PROCEDURE
5. STATEMENT TYPE COUNTS\(PROC)CALL\NONINTRINSIC
   <=> INVOCATIONS\PROCEDURE\NONINTRINSIC
6. STATEMENT TYPE COUNTS\(PROC)CALL\INTRINSIC
   <=> INVOCATIONS\PROCEDURE\INTRINSIC
7. AVG INVOCATIONS PER (CALLING) SEGMENT\NONINTRINSIC
   <=> AVG INVOCATIONS PER (CALLED) SEGMENT

By definition, the data scores obtained for any pair of duplicate aspects will be indentical, and thus the same statistical conclusions will be reached for both aspects.

Appendix 2. English Statements for the Non-Null Conclusions

The following numbered sentences simply provide English translations for the non-null location comparisons presented in symbolic equation form in Table 2.1. They may be skimmed by the reader since they do not add to the information appearing in the table.

(1) According to the SEGMENTS aspect, the individuals (AI) organized their software into noticeably fewer routines (i.e., functions or procedures) than either the ad hoc teams (AT) or the disciplined teams (DT).

(2) Both the ad hoc teams (AT) and the disciplined teams (DT) declared a noticeably larger number of data variables (i.e., scalars or arrays of scalars) than the individuals (AI), according to the DATA VARIABLES aspect.

(3) In particular, a definite trend toward this same difference was apparent in the number of global variables, the number of global variables whose values could be modified during execution, and the number of formal parameter variables, according to the DATA VARIABLE SCOPE COUNTS\GLOBAL, DATA VARIABLE SCOPE COUNTS\GLOBAL\MODIFIED, and DATA VARIABLE SCOPE COUNTS\NONGLOBAL\PARAMETER aspects, respectively.

(4) A trend existed for the individuals (AI) to have a smaller percentage of formal parameters compared to the total number of declared data variables than either the ad hoc teams (AT) or the disciplined teams (DT), according to the DATA VARIABLE SCOPE PERCENTAGES\NONGLOBAL\PARAMETER aspect.

(5) According to the AVERAGE NONGLOBAL VARIABLES PER SEGMENT\PARAMETER aspect, there was a trend for the individuals (AI) to have fewer formal parameters per routine than did either the ad hoc teams (AT) or the disciplined teams (DT).

(6) A definite trend existed for the individuals (AI) to have fewer possible segment-global usage pairs (i.e., potential access of a global variable by a routine) than either the ad hoc teams (AT) or the disciplined teams (DT), according to

the (SEG,GLOBAL) POSSIBLE USAGE PAIRS aspect.

(7) According to the AVERAGE STATEMENTS PER SEGMENT aspect, the individuals (AI) displayed a trend toward having a greater number of statements per routine than did either the ad hoc teams (AT) or the disciplined teams (DT).

(8) There existed slight trends toward more calls to programmer-defined routines per calling routine and per called routine for the individuals (AI) than for either the ad hoc teams (AT) or the disciplined teams (DT), according to the AVG INVOCATIONS PER (CALLING) SEGMENT\NONINTRINSIC and AVG INVOCATIONS PER (CALLED) SEGMENT aspects.

(9) In addition, a very slight trend existed for the individuals (AI) to have more calls to programmer-defined functions, averaged per programmer-defined function, than either the ad hoc teams (AT) or the disciplined teams (DT), according to the AVG INVOCATIONS PER (CALLED) SEGMENT\FUNCTION aspect.

(10) According to the DATA VARIABLE SCOPE PERCENTAGES\NONGLOBAL\LOCAL aspect, the individuals (AI) had a larger percentage of local variables compared to the total number of declared data variables than either the ad hoc teams (AT) or the disciplined teams (DT).

(11) A slight trend existed for both the individuals (AI) and the disciplined teams (DT) to have a larger relative percentage of segment-global usage pairs (i.e., the ratio of actual segment-global usage pairs to possible segment-global usage pairs) than the ad hoc teams (AT) for nonentry global variables whose values were not modified during execution (i.e., the simplest kind of "named constants"), according to the (SEG,GLOBAL) USAGE RELATIVE PERCENTAGES\NONENTRY\UNMODIFIED aspect.

(12) According to the STATEMENT TYPE COUNTS\IF and STATEMENT TYPE PERCENTAGE\IF aspects, both the individuals (AI) and the disciplined teams (DT) coded noticeably fewer IF statements than the ad hoc teams (AT), in terms of both total number and percentage of total statements.

(13) A trend existed, according to the STATEMENT TYPE COUNTS\(PROC)CALL\INTRINSIC aspect, for the ad hoc teams (AT) to make

a larger number of calls on intrinsic procedures (i.e., built-in language-provided routines primarily for input-output) than either the individuals (AI) or the disciplined teams (DT).

(14) According to the STATEMENT TYPE COUNTS\RETURN aspect, the ad hoc teams (AT) had a noticeably larger number of RETURN statements than either the individuals (AI) or the disciplined teams (DT).

(15) According to the DECISIONS aspect, both the individuals (AI) and the disciplined teams (DT) tended to code fewer decisions (i.e., IF, WHILE, or CASE statements) than the ad hoc teams (AT).

(16) A trend existed for the ad hoc teams (AT) to have more calls to intrinsic procedures, with a noticeably larger number of calls to intrinsic routines (i.e., built-in language-provided procedures and functions, primarily for input-output and type conversion), than either the individuals (AI) or the disciplined teams (DT), according to the INVOCATIONS\PROCEDURE\INTRINSIC and INVOCATIONS\INTRINSIC aspects, respectively.

(17) According to the (SEG,GLOBAL,SEG) DATA BINDINGS\POSSIBLE aspect, there was a slight trend for both the individuals (AI) and the disciplined teams (DT) to have fewer possible data bindings [Stevens, Myers, and Constantine 74] (i.e., occurrences of the situation where a global variable r is both potentially modified by a segment p and potentially accessed by a segment q, with p different from q) than the ad hoc teams (AT).

(18) According to the COMPUTER JOB STEPS aspect, the disciplined teams (DT) required very noticeably fewer computer job steps (i.e., module compilations, program executions, or miscellaneous job steps) than both the individuals (AI) and the ad hoc teams (AT).

(19) This same difference was definitely apparent in the total number of module compilations, the number of unique (i.e., not an identical recompilation of a previously compiled module) module compilations, the number of program

executions, and the number of essential job steps (i.e., unique module compilations plus program executions), according to the COMPUTER JOB STEPS\MODULE COMPILATIONS, COMPUTER JOB STEPS\MODULE COMPILATIONS\UNIQUE, COMPUTER JOB STEPS\PROGRAM EXECUTIONS, and ESSENTIAL JOB STEPS aspects, respectively.

(20) A trend existed for both the individuals (AI) and the ad hoc teams (AT) to have required more miscellaneous job steps (i.e., auxiliary compilations or executions of something other than the final software product) than the disciplined teams (DT), according to the COMPUTER JOB STEPS\MISCELLANEOUS aspect.

(21) According to the AVERAGE UNIQUE COMPILATIONS PER MODULE and MAX UNIQUE COMPILATIONS F.A.O. MODULE aspects, respectively, the disciplined teams (DT) required fewer unique compilations per module on the average, with a definite trend toward fewer unique compilations for any one module in the worst case, than either the individuals (AI) or the ad hoc teams (AT).

(22) According to the LINES aspect, there was a definite trend for the individuals (AI) to have produced fewer total symbolic lines (includes comments, compiler directives, statements, declarations, etc.) than the disciplined teams (DT) who produced fewer than the ad hoc teams (AT).

(23) A definite trend existed for the individuals (AI) to have a larger relative percentage of segment-global usage pairs for entry globals and for entry globals which could be modified during execution than the disciplined teams (DT) who had a larger still percentage than the ad hoc teams (AT), according to (SEG,GLOBAL) USAGE RELATIVE PERCENTAGES\ENTRY and (SEG,GLOBAL) USAGE RELATIVE PERCENTAGES\ENTRY\MODIFIED aspects, respectively.

(24) According to the PROGRAM CHANGES aspect, there existed a trend for the disciplined teams (DT) to require fewer textual revisions to build and debug the software than the individuals (AI) who required fewer revisions than the ad hoc teams (AT).

The following numbered sentences simply provide English translations for the non-null dispersion conclusions presented in symbolic equation form in Table 2.2. They may be skimmed by the reader since they do not add to the information appearing in the table.

(1) The individuals (AI) displayed noticeably less variation in the number of formal parameters passed by reference than both the ad hoc teams (AT) and the disciplined teams (DT), with a similar trend in the percentage of reference parameters compared to the total number of declared data variable, according to the DATA VARIABLE SCOPE COUNTS\NONGLOBAL\PARAMETER\REFERENCE and DATA VARIABLE SCOPE PERCENTAGES\NONGLOBAL\PARAMETER\REFERENCE aspects.

(2) According to the PARAMETER PASSAGE TYPE PERCENTAGES\VALUE and PARAMETER PASSAGE TYPE PERCENTAGES\REFERENCE aspects, both the ad hoc teams (AT) and the disciplined teams (DT) tended to have more variation in the percentage of value parameters and reference parameters compared with the total number of formal parameters declared than the individuals (AI).

(3) The individuals (AI) had less variation in the number of possible segment-global usage pairs (i.e., potential access of a global variable by a routine) involving nonentry globals than either the ad hoc teams (AT) or the disciplined teams (DT), according to the (SEG,GLOBAL) POSSIBLE USAGE PAIRS\NONENTRY aspect.

(4) According to the (SEG,GLOBAL,SEG) DATA BINDINGS\ACTUAL\INDEPENDENT aspect, there was a very slight trend for the individuals (AI) to have less variation in the number of actual data bindings [Stevens, Myers, and Constantine 74] (i.e., occurrences of the situation where a global variable r is both actually modified by a segment p and actually accessed by a segment q, with p different from q) in which the two routines were "independent" (i.e., neither segment can invoke the other, directly or indirectly) than both the ad hoc teams (AT) and the disciplined teams (DT).

(5) The individuals (AI) exhibited noticeably greater variation

than either the ad hoc teams (AT) or the disciplined teams (DT) in the number of miscellaneous job steps (i.e., auxiliary compilations or executions of something other than the final software project), according to the COMPUTER JOB STEPS\MISCELLANEOUS aspect.

(6) In the number of calls in general and of calls to programmer-defined routines in particular, the individuals (AI) displayed noticeably greater variation than both the ad hoc teams (AT) and the disciplined teams (DT), according to the INVOCATIONS and INVOCATIONS\NONINTRINSIC aspects.

(7) According to the STATEMENTS aspect, a very slight trend existed for the ad hoc teams (AT) to show less variability than either the disciplined teams (DT) or the individuals (AI) in the number of executable statements.

(8) A trend existed for both the individuals (AI) and the disciplined teams (DT) to have greater variability than the ad hoc teams (AT) in the average (per function) number of calls to programmer-defined functions, according to the AVG INVOCATIONS PER (CALLED) SEGMENT\FUNCTION aspect.

(9) According to the (SEG,GLOBAL) ACTUAL USAGE PAIRS\MODIFIED aspect, a definite trend existed for the ad hoc teams (AT) to have less variability than either the individuals (AI) or the disciplined teams (DT) in the number of actual segment-global usage pairs (i.e., actual access of a global variable by a routine) involving globals which were modified during execution.

(10) According to the AVERAGE SEGMENTS PER MODULE aspect, the individuals (AI) and the disciplined teams (DT) both exhibited noticeably less variation in the average number of routines per module than the ad hoc teams (AT).

(11) The ad hoc teams (AT) were noticeably more variable than either the disciplined teams (DT) or the individuals (AI) in the percentage of coded RETURN statements compared with the total number of statements, according to the STATEMENT TYPE PERCENTAGES\RETURN aspect.

(12) According to the AVERAGE GLOBAL VARIABLE PER MODULE\MODIFIED aspect, the ad hoc teams (AT) displayed a definite trend

toward greater variability than both the individuals (AI) and the disciplined teams (DT) in the average number of globals per module which were modified during execution.

(13) The individuals (AI) and the disciplined teams (DT) were both noticeably less variable than the ad hoc teams (AT) in the number of possible segment-global usage pairs where the global variable was nonentry and modified during execution, according to the (SEG, GLOBAL) POSSIBLE USAGE PAIRS\NONENTRY\MODIFIED aspect.

(14) According to the (SEG,GLOBAL,SEG) DATA BINDINGS\POSSIBLE aspect, the ad hoc teams (AT) tended toward greater variability than either the individuals (AI) or the disciplined teams (DT) in the number of possible data bindings.

(15) According to the STATEMENT TYPE COUNTS\(PROC)CALL, STATEMENT TYPE COUNTS\(PROC)CALL\NONINTRINSIC, INVOCATIONS\PROCEDURE, and INVOCATIONS\PROCEDURE\NONINTRINSIC aspects, both the individuals (AI) and the ad hoc teams (AT) were noticeably more variable than the disciplined teams (DT) in the number of calls to intrinsic and nonintrinsic procedures, with a similar trend for calls to nonintrinsic procedures alone.

(16) This same difference appeared in the average number of intrinsic procedure calls per calling segment, according to the AVG INVOCATIONS PER (CALLING) SEGMENT\PROCEDURE\INTRINSIC aspect.

(17) According to the DATA VARIABLES SCOPE PERCENTAGES\GLOBAL\NONENTRY\MODIFIED aspect, the disciplined teams (DT) displayed noticeably smaller variation than either the individuals (AI) or the ad hoc teams (AT) in the percentage of nonentry global variables that were modified during execution compared to the total number of data variables declared.

(18) According to the AVERAGE TOKENS PER STATEMENT aspect, a definite trend existed for the disciplined teams (DT) to exhibit greater variability in the average number of tokens (i.e., basic symbolic units) per statement than both the individuals (AI) and the ad hoc teams (AT).

(19) The trend toward less variation among both the individuals

(AI) and the ad hoc teams (AT) than among the disciplined teams (DT) existed in the number of global variables and in the number of formal parameters, according to the DATA VARIABLE SCOPE COUNTS\GLOBAL and DATA VARIABLE SCOPE COUNTS\NONGLOBAL\PARAMETER aspects, respectively.

(20) A similar difference in variability existed noticeably in the percentages, compared to the total number of declared data variables, of globals, of nonglobals, of formal parameters, and of formal parameters passed by value, according to the DATA VARIABLE SCOPE PERCENTAGES\GLOBAL, DATA VARIABLE SCOPE PERCENTAGES\NONGLOBAL, DATA VARIABLE SCOPE PERCENTAGES\NONGLOBAL\PARAMETER, and DATA VARIABLE SCOPE PERCENTAGES\NONGLOBAL\PARAMETER\VALUE aspects, respectively.

(21) According to the (SEG,GLOBAL) POSSIBLE USAGE PAIRS and (SEG,GLOBAL) POSSIBLE USAGE PAIRS\NONENTRY\UNMODIFIED aspects, there was a noticeable difference in variability, with the individuals (AI) less than the disciplined teams (DT) less than the ad hoc teams (AT), for the total number of possible segment-global usage pairs, with a similar trend for possible usage pairs in which the global variable was nonentry and not modified during execution.

(22) There was a noticeable difference in variability, with the disciplined teams (DT) less than the individuals (AI) less than the ad hoc teams (AT), in the maximum number of unique compilations for any one module, according to the MAX UNIQUE COMPILATIONS F.A.O. MODULE aspect.

(23) According to the STATEMENT TYPE COUNTS\RETURN aspect, there was a difference in variability, with the disciplined teams (DT) less than the individuals (AI) less than the ad hoc teams (AT), for the number of RETURN statements coded.

Appendix 3. English Paraphrase of Relaxed Differentiation Analysis

The following two paragraphs simply provide an English paraphrase of the "relaxed differentiation" details presented in Tables 4.1 and 4.2, respectively.

On *location* comparisons, four programming aspects yielded completely differentiated conclusions. They are "relaxed" to partially differentiated conclusions as follows:

1. From DT < AI < AT on PROGRAM CHANGES, the DT < AI = AT conclusion overwhelmingly dwarfs the DT = AI < AT conclusion
2. The DT < AT difference is more pronounced than the AI < DT difference from AI < DT < AT on LINES
3. AT < DT < AI on (SEG,GLOBAL) USAGE RELATIVE PERCENTAGES\ENTRY is more significantly "relaxed" to AT < DT = AI than to AT = DT < AI
4. The AT < DT and DT < AI differences from AT < DT < AI on (SEG,GLOBAL) USAGE RELATIVE PERCENTAGES\ENTRY\MODIFIED are both exactly equally strong

On *dispersion* comparisons, three programming aspects yielded completely differentiated conclusions. They are "relaxed" to partially differentiated conclusions as follows:

1. The DT < AI difference is much more pronounced than the AI < AT difference from DT < AI < AT on MAX UNIQUE COMPILATIONS F.A.O. MODULE
2. From DT < AI < AT on STATEMENT TYPE COUNTS\RETURN, the DT = AI < AT conclusion overwhelmingly dwarfs the DT < AI = AT conclusion
3. AI < DT < AT on (SEG,GLOBAL) POSSIBLE USAGE PAIRS is more significantly "relaxed" to AI < AT = DT than to DT = AI < AT
4. The AI < DT difference is more pronounced than the DT < AT difference from AI < DT < AT on (SEG,GLOBAL) POSSIBLE USAGE PAIRS\NONENTRY\UNMODIFIED

Appendix 4. English Categorization of Directionless Distinctions

The following two paragraphs provide a complete itemization of directionless distinctions. The information contained in Tables 2 and 4 has simply been reorganized and presented in English to support a directionless view of the study's results.

Specifically, for the study's location comparisons:

(1) The distinction

AI (individuals) ≠ AT (ad hoc teams) = DT (disciplined teams)

was observed for none of the process aspects and for several product aspects, including

- the raw count of programmer-defined segments (i.e., routines),
- the raw count of programmer-defined data variables,
- several raw counts and relative percentages of data variables according to their scope (i.e., global, parameter, or local),
- the raw count of potential segment-global usage pairs (which is strongly dependent on the raw counts of segments and globals, both of which are also in this category), and
- several "per segment" averages of other raw counts (i.e., formal parameters, executable statements, and nonintrinsic calls).

(2) The distinction

AT (ad hoc teams) ≠ DT (disciplined teams) = AI (individuals)

was observed for none of the process aspects and for several product aspects, including

- the raw count of lines of symbolic source code,
- both the raw count and relative percentage of IF statements,
- the raw count of programmed decisions (i.e., total number of IF, CASE, and WHILE statements),
- the raw count of RETURN statements,
- the raw counts of calls to intrinsic routines and intrinsic

procedures,

- one ratio of actual to possible accessibility of globals by segments, and
- the raw count of possible communication paths between segments via globals.

(3) The distinction

DT (disciplined teams) ≠ AI (individuals) = AT (ad hoc teams)

was observed for nearly all the process aspects, including

- nearly all the raw counts of computer job steps, including both the total count and all the subclassification counts (i.e., compilations, executions, miscellaneous), except for identical compilations,
- both "per module" counts of unique compiles, the average and the (worst case) maximum, and
- the amount of revision and change made to the source code during development,

but for none of the product aspects.

Specifically, for the study's dispersion comparisons:

(1) The distinction

AI (individuals) ≠ AT (ad hoc teams) = DT (disciplined teams)

was observed for one process aspect, namely

- the raw count of miscellaneous computer job steps (i.e., auxiliary compilations or executions of something other than the final product),

and for several product aspects, including

- the raw count and several relative percentages of reference parameters,
- a few raw counts of potential segment-global usage pairs,
- the raw count of total invocations and invocations of programmer-defined routines, and
- the raw count of actual segment-global-segment data bindings in which neither segment could invoke the other.

(2) The distinction

AT (ad hoc teams) ≠ DT (disciplined teams) = AI (individuals)

was observed for none of the process aspects and for several product aspects, including

- two "per module" averages of other raw counts, (i.e., segments and global variables which were modified during execution),
- the raw count of executable statements,
- both the raw count and relative percentage of RETURN statements,
- the average number of calls made to programmer-defined segments which were functions rather than procedures,
- the raw count of actual segment-global usage pairs in which the global variable is modified during execution,
- the raw count of potential segment-global usage pairs in which the global variable is not accessible across modules and is modified, and
- the raw count of potential segment-global-segment data bindings.

(3) The distinction

DT (disciplined teams) $\neq$ AI (individuals) = AT (ad hoc teams)

was observed for one process aspect, namely

- the (worst case) maximum count of unique compiles for any one module,

and for several product aspects, including

- several raw counts and relative percentages of data variables according to their scope (i.e., global, parameter, or local),
- the raw counts of calls to procedures and to programmer-defined procedures,
- the average number of calls to built-in procedures per calling segment, and
- the average number of tokens per statement.